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**Mental and perceptual
performance in heat**

Curt R Johansson

**National Swedish
Building Research**



Mental och perceptuell prestation i värme

Prestationsförändringar i värme och sambandet mellan dem och fysiologisk belastning, värmeupplevelse, prestationsförmåga och personlighetsfaktorer

Curt Johansson

En litteraturgenomgång av värmestressforskningen visade att mentala, perceptuella och psykomotoriska prestationer huvudsakligen studerats i laboratorieexperiment, varvid försökspersonerna varit värmeacklimatiserade unga män i god fysisk kondition. De har vanligtvis förtränats på de uppgifter som använts och har därför behärskat uppgifterna väl innan de värmebelastats. Expositionstiden har varierat från mindre än en timme till flera timmar. Forskningsintresset har under senare år förskjutits från ett kartläggande av sambandet mellan konstant omgivningstemperatur och prestation till ett studium av prestationsförändringar betingade av varierande rumstemperaturer eller av reglerade kroppstemperaturökningar.

Litteraturgenomgången visade att när omgivningstemperaturen överstiger 30 °C ET, och försökspersonerna är iklädda endast shorts, försämras med stor sannolikhet mentala, perceptuella och psykomotoriska prestationer. Ett kritiskt område utgör temperaturintervallet 27–30 °C ET. Något generellt samband mellan rumstemperatur och prestationsförändring har ej kunnat påvisas. Däremot har ett linjärt samband konstaterats i flertalet undersökningar av mentala prestationer, medan ett kurvlinjärt samband föreläggat för perceptuella prestationer. Ett optimalt har därvid nåtts i temperaturintervallet 24–27 °C ET.

I de tidigare undersökningarna angavs ofta att något orsakssamband ej förelåg mellan kroppstemperatur och prestation. Nyare undersökningar, som studerat prestationsförändringar som en funktion av kontrollerad hypertermi, har emellertid visat att prestationen försämras under värmebelastning när kroppstemperaturen överstiger 38 °C. Beträffande kontorsbetonat arbete synes en konstant rumstemperatur vara att föredraga framför ett klimat med varierande rumstemperatur.

Det har påvisats att även om stark motivation kan öka prestationen under värmebelastning kan dock inte värmebetingade prestationsförsämringar motverkas. Vidare har det konstaterats att

prestationen i värme försämras mest för försökspersoner som arbetar på gränsen av sin förmåga eller som arbetar med stor ansträngning.

En psykofysiologisk modell med relevans för värmestressforskning presenteras. Den anger att vakenhetsnivån vid värmebelastning är en funktion av såväl centralnervösa som perifera neuronala mekanismer. En vakenhetssänkning inträder förmodligen när organismtemperaturen ökar något över den habituella basnivån, medan en ytterligare ökning av organismtemperaturen antages vara vakenhetshöjande. Modellen förutsäger att flertalet prestationer, med undantag för vissa perceptuella prestationer, försämras under måttlig värmebelastning till följd av den då uppträdande vakenhetssänkningen och under svårare värmebelastning till följd av den antagna vakenhetshöjningen. För sådana perceptuella uppgifter som mäter uppmärksamhetsfördelningen (cue-utilization) förväntas ett omvänt U-format samband föreligga mellan värmebelastning och prestation, medan sambandet förväntas vara U-format för vigilanceuppgifter som mäter förmågan att rikta uppmärksamheten mot vissa signaler i omgivningen.

Värmeframkallade fysiologiska och psykologiska reaktioner samt sambandet mellan dem och mentala och perceptuella prestationer studerades i en experimentell undersökning. Tjugofyra tioåriga skolbarn i en experimentgrupp värmebelastades iklädda shorts vid 30 °, 36 ° och 41 °C DB. Barnen exponerades för samtliga tre klimat i slumpmässig ordning, varvid expositionstiden vid varje försök var tre timmar. Eftersom luftförehastigheten var 0,3 m/s och vattenångtrycket var 15 mm Hg motsvarar de tre klimatbetingelserna 0, 0,6 och 1,2 P4SR eller 24 °, 27 ° och 29 °C ET. En kontrollgrupp om 12 barn exponerades på övrigt likartade betingelser för 0 P4SR. Samtliga barn testades, innan de deltog i värmeförsöken, med avseende på allmänbegåvning, prestationsförmåga och personlighetsfaktorer.

På grundval av de erhållna resultaten drogs följande slutsatser.

1. Inomhusklimat motsvarande 0,6 el-

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ler 1.2 P4SR bör ej förekomma i skolbyggnader. Den värmebelastning som dessa klimatbetingelser förorsakade ytttrade sig som statistiskt signifikanta öknin-
 10 g av fysiologiska och psykologiska belastningsreaktioner och försämringar av mentala prestationer.

Den ökade svettningen vid 0.6 P4SR kan resultera i att beklädnaden blir fuktig och ohälsosam samt att också obehaglig kroppslukt kan uppstå. Vid 1.2 P4SR kan den termiska balansen i kroppen rubbas varför detta klimat måste anses utgöra belastningsgräns vid långvarig värmeexposition. Flertalet försökspersoner upplevde också 1.2 P4SR som "för varmt, mycket för varmt, eller hett".

2. Belastningseffekter på värmebalanssystem och på olika prestationer förelåg redan efter en kort stunds värmeexposition och de utvecklades till full styrka under den första försökstimmen. Beträffande kroppstemperatur och svettning konstaterades små öknin-
 10 g av dessa fysiologiska belastningsmått under försöken, medan inga sådana effekter förelåg för pulsfrekvens och prestation.

Dessa resultat stöder ej hypotesen att värmebetingade prestationsförändringar är beroende på en successivt ökande värmetrötthet. Det synes vara mera troligt att prestationsförändringar i värme förorsakas av en funktionell omorganisering av värmebalanssystemet; en omorganisering som sannolikt påverkar CNS.

3. Rektaltemperaturen befanns vara det bästa och svettningen det sämsta fysiologiska värmebelastningsmålet. Det var emellertid inte möjligt att förutsäga rektaltemperaturen i värme utifrån den

habituella vilonivån vid 0 P4SR.

4. Statistiskt säkerställda prestationsförsämringar om 10 % konstaterades på ett additionstest och på ett multiplikationstest (se FIG. 1 a). Barnen var förtrogna med dessa uppgifter från skolarbete och de hade också förtränats på 'dem. Prestationsförsämringarna var ej relaterade till graden av fysiologisk eller psykologisk belastning, allmänbegåvning eller personlighet.

Det förelåg inte något orsakssamband mellan rektaltemperatur under 38 °C och prestationsförändring på de numeriska uppgifterna. Även om resultaten i övrigt stod i överensstämmelse med den framställda teoretiska modellen var det emellertid oklart genom vilken mekanism eller på vilket sätt prestationsförändringarna framkallades.

5. Ett omvänt U-format samband mellan värmebelastning och uppmärksamhetsfördelning förelåg för samtliga försökspersoner (se FIG. 1 b). Därmed antyd-
 10 des att oberoende av försökspersonernas individuella egenskaper var deras prestation på två uppmärksamhetsprov bäst vid måttlig värmebelastning. Det stöder den teoretiska modellen men utgör inget avgörande bevis för att den är korrekt, eftersom vakenhetsnivån ej registrerades elektrofysiologiskt.

6. Det förelåg ett starkt samband mellan rektaltemperatur och prestationsförsämring på sådana uppgifter som försökspersonerna ej förtränats på och därför ej var förtrogna med. Detta samband var starkast om rektaltemperaturen angavs som förändringen från den habituella vilonivån i stället för som absolut mått.

I motsats till de förtränade numeriska

proven förelåg sålunda för de ej förtränade uppgifterna sannolikt ett orsakssamband mellan kroppstemperaturökning och prestationsförsämring. Eftersom tekniken i utförandet av dessa uppgifter måste läras in under värmeförsöken är det troligt att denna inläring av hur uppgifterna skulle utföras var känslig för en ökning av den fysiologiska belastningen. Det bör understrykas att om en sådan inläring sker för försökspersoner som ej är nämnvärt fysiologiskt påverkade kan denna inläringseffekt neutralisera prestationsförsämringar för fysiologiskt starkt belastade försökspersoner i en undersökningsgrupp.

7. Prestationsförändringarna i värme var relaterade till försökspersonernas prestationsförmåga. Starkast påverkade var de barn som arbetade på toppen av sin förmåga, till följd av att de precis lärt sig en uppgift utan att helt behärska den.

8. Parametriska och icke-parametriska variansanalyser visade att de värmebetingade prestationsförändringarna uppträdde oberoende av försökspersonernas allmänbegåvning eller personlighet och oberoende av hur de upplevde klimatet. För vissa av de försökspersoner, vars prestationer försämrades, kunde emellertid genom en Q-faktoranalys konstateras att de skilde sig från andra försökspersoner genom mönstret i allmänbegåvning, personlighet och klimatupplevelse.

9. Klimatupplevelsen var ej relaterad till rektaltemperaturen och därmed antyd-
 10 des att försökspersonerna kunde skatta omgivningstemperaturen oberoende av den egna kroppstemperaturen.

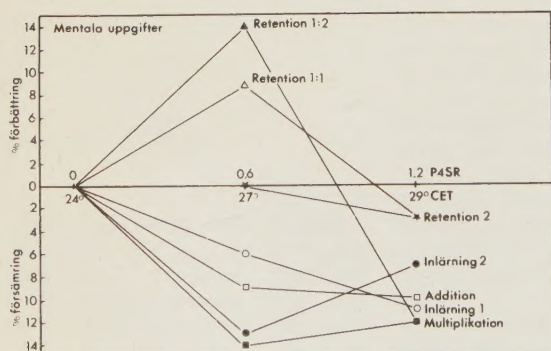


FIG. 1a. Mentala prestationsförändringar under värmebelastning

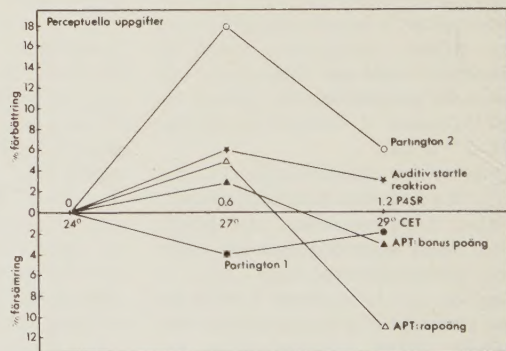


FIG. 1b. Perceptuella prestationsförändringar under värmebelastning

Mental and perceptual performance in heat

Heat-induced performance changes and their relation to physiological strain, thermal sensation, ability and personality factors

Curt Johansson

A review of heat-stress studies suggested that mental, perceptual, and psychomotor tasks have mainly been studied in laboratory experiments performed on heat acclimatized fit young men. The subjects were usually given extensive practice on the performance tasks, which were well learnt prior to heat load. The exposure time varied from less than one hour to several hours.

The emphasis recently shifted from an exploration of the relation between constant ambient temperature and performance to studies of performance changes under controlled hyperthermia or as a function of ambient temperature swings.

The reviewed studies indicated that an ambient temperature exceeding 30 °C ET will probably impair the performance on mental, perceptual, and psychomotor tasks for subjects stripped to the waist. A critical zone exists between 27 ° and 30 °C ET. No general relation between ambient temperature and performance change has been found. However, in most studies of mental tasks, the relation was linear, whereas for perceptual but non-motor tasks it was curvilinear and optimum performance was achieved at 24–27 °C ET.

Previous studies often reported no causal relation between body temperature and performance, whereas recent studies of performance under controlled hyperthermia have shown that adverse performance changes under heat load occur when the body temperature exceeds 38 °C. For sedentary work, a constant climate seems preferable to ambient temperature swings.

Even if a high degree of motivation increases the performance under heat load, it has been shown that the adverse effects of heat stress on performance are not counteracted. Moreover, subjects working at optimum effort and those working at the limit of their ability were to be most easily adversely influenced by environmental warmth.

A psychophysiological model was proposed suggesting that under heat load the level of arousal is a function of both central and peripheral neural factors. D arousing effects will probably appear when the organic temperature is slightly increased above the ordinary base level. A further increase of the organic temperature will be arousing. According to

this model, most tasks, except cue-utilization and similar perceptual and non-motor tasks, will be impaired under moderate heat load owing to underarousal, and under heavy heat load owing to overarousal. Perceptual tasks measuring cue-utilization and attention will display an inverted U-shaped trend, whereas for signal detection tasks, a direct U-shaped trend is predicted.

Heat-induced physiological and psychological strain and its relation to mental and perceptual performance was investigated in an experimental study. For three hours, on each of three occasions, an experimental group of 24 ten-year-old school children, dressed in shorts, were exposed to 30 °, 36 °, and 41 °C DB in random order. As the air speed was 0.3 m/sec and the water-vapour pressure 15 mm Hg, the three climate conditions corresponded to 0.6, and 1.2 P4SR or 24 °, 27 °, and 29 °C ET. With the same procedure, a control group of 12 children were exposed to 0 P4SR. Before heat exposure, the subjects were tested for general intelligence, skill, and personality characteristics.

Based on the results in the experimental study, the following conclusions were drawn.

1. An indoor climate of 0.6 or 1.2 P4SR should be avoided in school buildings because the thermal load of these climates gave rise to significant increases in physiological and psychological strain, and mental performance was adversely affected.

An increased sweat rate at 0.6 P4SR can make the clothing damp and insalubrious and could give rise to bad odour. At 1.2 P4SR, the thermal equilibrium limit might be exceeded, and can be regarded as the maximum tolerable for prolonged heat exposure. Most subjects also perceived 1.2 P4SR as "too warm, much too warm", or "hot".

2. The effects of heat load on the thermoregulatory system and on performance were displayed after a short period of exposure. They reached almost full strength during the first hour of exposure. Small progressively increasing effects were noted with respect to rectal temperature and gross sweat rate, g/h, whereas no such effects were found with respect to pulse rate and performance.

These facts do not support the hypothesis that changes in performance are associated with thermal fatigue. A more

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plausible explanation seems to be that performance changes under heat load are dependent on a functional reorganization of the thermoregulatory system. This autonomous reorganization probably influences the functioning of the CNS.

3. The rectal temperature was found to be the most consistent and reliable measure of physiological strain, whereas sweating less accurately indicated changes in physiological strain. However, the degree of physiological strain under heat load could not be predicted for rectal temperature from knowledge of the resting base level at 0 P4SR.

4. In practised tasks such as addition and multiplication, reliable main effects of heat appeared to indicate that the performance was reduced by about 10 % (see FIG. 1a). These effects occurred independent of the degree of physiological and psychological strain, general intelligence, and personality, both separately and in combination.

The findings indicated that there was no direct causal relation between rectal temperature below 38 °C and change of performance in practised tasks. The nature of the mechanism causing heat-induced impairment in such tasks is not clear, although the results were in accordance with the heat-stress-arousal model outlined.

5. An inverted U-shaped relation between heat load and attention was found for all subjects and was not associated with individual characteristics (see FIG. 1b). This quadratic trend, indicating that an optimum cue-utilization was achieved at moderate heat load and physiological strain, supported the suggested theoretical model. However, as level of arousal was not measured electrophysiologically, no conclusive evidence was found in support of the model.

6. The performance changes in not practised tasks were strongly associated with the degree of physiological strain and in particular with the heat-induced deviation in rectal temperature from its base level at 0 P4SR. Performance changes were less predictable with physiological strain expressed by means of absolute measures instead of deviation measures.

Thus, in contrast to practised tasks, a causal relation seems to exist between deviation in rectal temperature and performance in not practised tasks. Such tasks have to be learnt before the subject can perform them efficiently. This learning-how-to-learn process is sensitive to an increase in physiological strain. It must be emphasized that, if learning-how-to-learn effects are operating, adverse effects for subjects under physiological strain could be neutralized by learning effects for physiologically

unaffected subjects.

7. In addition to physiological strain, skill was consistently associated with heat-induced changes of performance. Subjects working at the limit of their ability, because they had recently acquired, but not completely mastered, the technique of performing a new task, were most adversely affected by heat.

8. Parametric and non-parametric analyses of variance indicated that the effects of heat load were independent of thermal sensation and of individual characteristics such as general intelligence and personality analysed separately.

However, Q-factor analyses made clear that some combinations of these factors can be characteristic for adversely affected subjects.

9. The fact that thermal assessments of the climate were not associated with rectal temperature indicated that heat stress might be rated without confounding with heat strain. It also indicated that thermal assessment of the environmental warmth would not be used as a measure of heat-induced psychological strain. Such a measure would, instead, be based on assessment of both heat stress and physiological strain.

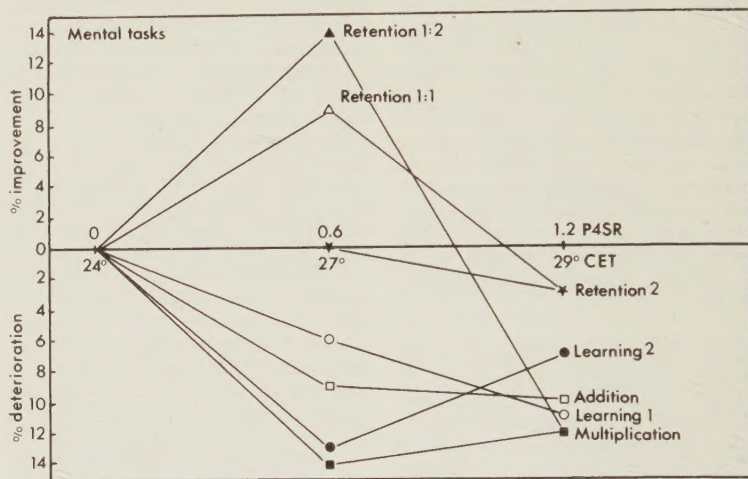


FIG 1a. Mental performance changes under heat load

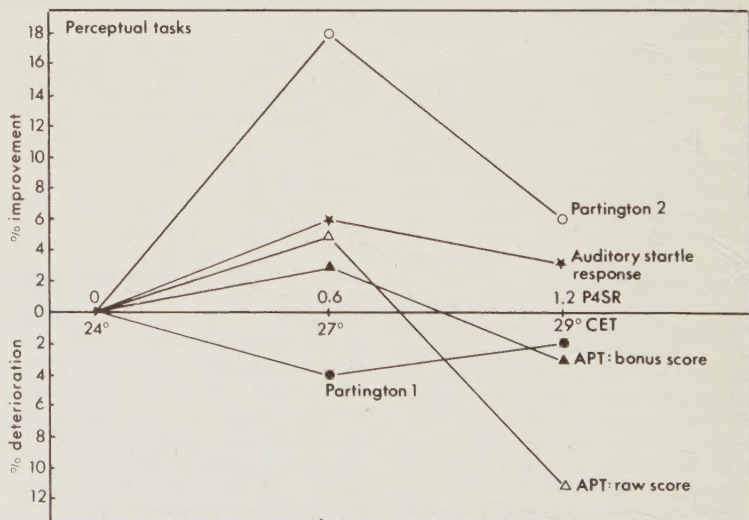


FIG 1b. Perceptual performance changes under heat load

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MENTAL AND PERCEPTUAL PERFORMANCE IN HEAT

Heat induced performance changes and their relation to physiological strain, thermal sensation, ability and personality factors

Curt R Johansson

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ABSTRACT

CURT R JOHANSSON, 1975. MENTAL AND PERCEPTUAL PERFORMANCE IN HEAT.

Heat-induced performance changes and their relation to physiological strain, thermal sensation, ability, and personality factors

On the basis of a literature review, it was concluded that an ambient temperature exceeding 30°C ET will most likely impair the performance on mental, perceptual, and psycho-motor tasks. A critical zone exists between 27° and 30°C ET.

For mental tasks, a linear relation seems to exist between heat stress and change of performance. In most studies of perceptual tasks, a curvilinear trend has appeared with optimum performance achieved at 24° - 27°C ET. Recent studies have shown that adverse performance changes occur when the body temperature exceeds 38°C .

Physiological strain, thermal sensation, and mental and perceptual performance of 24 10-year-old school children were investigated during exposure to environmental heat in a climate chamber. The subjects were dressed in shorts and attended singly on three separate occasions. They experienced 30° , 36° , and 41°C for three hours in each temperature at an air movement of 0.3 m/sec and a water vapour pressure of 15 mm Hg . These conditions, corresponding to 0, 0.6, and 1.2 P4SR or 24° , 27° , and 29°C ET, were presented in a balanced order. A control group of 12 subjects met the thermally neutral 0 P4SR condition three times; otherwise, they were subjected to the same procedure as for the experimental group.

Rectal temperature, pulse rate, and sweat rate were significantly increased under thermal load. At 1.2 P4SR , the thermal equilibrium limit— 38°C rectal temperature—was exceeded, and most subjects found this climate "too warm, much too warm, or hot." The physiological heat strain effects and heat-induced performance changes appeared after a short period of exposure. Independent of physiological and psychological strain, general intelligence, and personality, adverse effects of heat averaging 10% appeared on practised numerical tasks, whereas an inverted U-shaped relation was found between heat load and perceptual performance. On unpractised tasks, a marked linear relation existed between performance and rectal temperature, implying that adverse effects were noted for physiologically affected subjects, whereas learning-how-to-learn effects appeared for unaffected subjects. Skill was

consistently associated with the heat-induced performance changes. These were explained in terms of a stress-strain-arousal model.

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INTRODUCTION

BACKGROUND

All living organisms, including plants, are dependent on their environment for survival. However, although all life is more or less restricted to a special environment, most plants and organisms can, within certain limits, adapt to environmental changes of different kinds. The climate is one of the most important fluctuating environmental factors, which varies cyclically during the twentyfour hours resulting in a warm, bright, and noisy day, on one hand, and a cool, dark, and silent night, on the other. The thermal environment also varies with the seasonal changes, creating temperature differences of about 70°C between winter and summer in continental climates.

The behaviour and functioning of poikilotherms, such as snakes and frogs follow the temperature changes. This is because the tissue temperature of these animals varies directly with the surrounding temperature. Man, similar to other homeotherms, is not so functionally dependent on and tissually vulnerable to thermal changes, as are poikilothermal organisms, even though each homeothermal organism makes specific demands on its climate. This is mainly because the homeotherms have a well-developed and effective thermoregulatory system, which controls and preserves a stable body temperature and constant internal bodily functioning.

Distinct from other homeotherms, Man has also increased his capacity to withstand a wide range of environmental conditions due to his ability to exploit different forms of energy for air-conditioning and to invent and use protective clothing and dwellings. Modern engineering enables

Man to live and work not only on Earth but also in the extreme conditions prevailing in space and on the Moon. In view of this, it is surprising that modern building engineers and architects often fail to create a good indoor climate.

Early in his history, Man lived and performed most of his activities in the open. To some extent, he could protect himself against weather and wind in caves, (igloos), or wigwams, where he could slightly modify the indoor climate by using fire. The fire provided both warmth and light, besides its use for cooking, work, and protection against predatory animals. Although in classical times the Romans invented the technique of central heating by steam ducted through channels in the walls, the open fire was the commonest way of heating dwellings before the industrial revolution. However, clothing was for long Man's main means of protecting himself against environmental heat and cold, and of adapting to the climate. The invention of the heater and the development of hot-water circulation systems during the nineteenth century made central heating a common way of warming houses in many countries.

At about the same time, Man had recognized and learnt to measure the four environmental components that determine the climate; namely, temperature, humidity, and speed of the air, and also radiant temperature. In order to compensate for environmental warmth during the summer, the air-conditioning technique was later developed using refrigerating systems. Consequently, Man is not longer obliged to wear protective clothing indoors to compensate for the climate and its cyclical and random changes. Instead, Man now tends to wear a uniform dress indoors, where he creates a constant climate by means of modern regulating technique. Since the cost of central heating and air-conditioning is high and Man nowadays performs most of his activities

indoors, it is important to know what constitutes an optimum climate for well-being and performance.

For the physiologist studying the reactions of Man under climate stress, the thermoregulatory strain reactions of sweating, circulation, pulse rate, and body temperature are of basic concern. In order to be able to prevent Man from exposure to intolerable and dangerous climates, the physiologist must know and understand not only how different aspects of the climate, such as air and radiant temperature, air humidity, and air speed, affect Man, but also how age, sex, physical fitness, and the acclimatization of the subject influence his physiological strain reactions, for instance, body temperature, pulse rate, and sweating. Work rate and clothing must also be considered, because these factors affect the thermal stress of the climate.

To integrate the effects of factors contributing to thermal stress, a large number of indices have been proposed. Besides studying Man's physiological strain reactions, the climatologist also investigates Man's well-being. During the end of the nineteenth century, research on thermal comfort began to increase and reached its peak around 1920-1930 with the derivation of the "Effective Temperature" scale (ET-scale; see below Previous reviews and hypotheses on the effects of heat stress on performance). Initiated by military and industrial requirements for increased working efficiency during the First World War, researchers also began to investigate Man's physical and mental performance in different thermal conditions. This ergonomic research, based on interdisciplinary work between engineering, physiology, and psychology, developed tremendously during the Second World War and is still in progress. Performance is usually related to the physical factors of the climate, ignoring its self-evident dependence on bodily strain reactions

and their changes during prolonged exposure.

The psychologist investigating mental performance under climate stress must consider not only the physical properties of the climate but also Man's bodily reactions together with his individual comfort sensation. In addition, such individual characteristics as ability and personality play a part in determining how different subjects react and perform under imposed heat stress. Individual characteristics have usually been treated as uncontrollable error variables in the design and analysis of climate studies. Their influence on the results has therefore often been removed instead of being studied separately, and the extent of their influence is as yet unknown.

In 1967, a very extensive research programme on the indoor climate in Swedish schools and its effects on the performance and behaviour of school children was initiated by the National Swedish Building Research Institute. Previous measurements of climate in schools had revealed that high environmental temperatures are a common hygienic problem (Boysen *et al.* 1967 a). Air temperatures in the 27-33°C range were measured in many schools. Teachers' ratings of the classroom climate indicated that they generally prefer a temperature of 18-22°C and that they often report thermal discomfort when the ambient temperature exceeds 25°C (Boysen *et al.* 1967 b). Thermal discomfort is often caused by attempts to provide good daylight illumination, which in turn leads to the admission of direct solar radiation and to high indoor air temperature. Despite complaints from teachers about overheating in classrooms which, it is suggested, impairs mental performance (Mc Donald 1960) no experimental investigations had completely established the relation between thermal stress and strain immediately above the comfort zone around 27°C

dry bulb (DB) air temperature.

The Swedish research programme was initiated to provide this information. It consisted of both field studies in schools and experimental laboratory studies. The results of the field studies have since been published by Wyon (1969, 1970), Holmberg & Wyon (1969, 1972) and Ryd & Wyon (1970). These studies related the changes in mental performance and behaviour to the climate stress caused by high classroom temperatures. The experimental studies presented in the present report concern complementary measurements of mental performance and physiological strain during heat exposures in a climate chamber. The general questions posed by this study were:

- 1) To what extent are school children physiologically and mentally affected by exposure to the levels of moderate heat stress that have been found in Swedish schools?
- 2) Is mental performance related to physiological strain?
- 3) Do ability and personality factors *per se*, influence the effects of heat on mental performance?
- 4) What characteristics can be identified in children whose performance is adversely affected by heat, as opposed to unaffected children?

Figure 6 presents the research paradigm in full.

REVIEW OF RELEVANT LITERATURE

During the past 20 years, several reviews have been published on heat stress research covering the physiological as well as the psychological effects of thermal exposure (Provins 1958, Bedford 1953, 1961, Hardy 1961, Provins & Bell 1962, Bell & Provins 1962, Macpherson 1962, Pepler 1963, 1964, Broadbent 1963 a,

Leithhead & Lind 1964, Löfstedt 1965, 1966, Wing 1965, Provins 1966).

There is a total absence of studies of children under imposed heat stress. Most investigations on thermal stress have been conducted in order not to exceed physiological tolerance limits in industrial and military working conditions. The subjects have been heat acclimatized young men, usually working on well-practised physical or psycho-motor tasks. The results of these studies cannot be applied directly to the school situation, to children predominantly engaged in sedentary mental work.

The results were contradictory and ambiguous, making it more difficult to draw general conclusions about the effects of heat on performance. To some extent, this may be because the research was focused on specific practical problems. Consequently, the knowledge obtained was not theoretically accumulated and integrated to form a model or theory with respect to physiological function, behaviour, performance, and well-being; a model from which a logical set of hypotheses could be deduced and from which research results could be interpreted and evaluated.

Previous reviews and hypotheses on the effects of heat stress on performance

Although much research has been carried out on the effects of heat stress on performance, no clear view has emerged on how Man's performance is affected. However, most reviewers agree that performance is usually adversely affected by environmental heat exceeding about 30°C ET (Provins 1958, Bell & Provins 1962, Pepler 1963, 1964). Several difficulties in the design and analysis of heat stress research add to the confusion about how and to what extent Man's

performance is affected. One of these difficulties is the lack of agreement on how the total heat load of the environment should most adequately be described and measured. Air velocity, the humidity of the air, and the radiant temperature in addition to air temperature, play a part in determining imposed heat stress.

Indices of heat stress

Based on comfort ratings by only three resting subjects, Houghten & Yagloglou (1923) attempted to construct a thermal index, taking account of both air temperature and humidity. In a later study by Houghten & Yagloglou (1924) performed on the same number of subjects, the effect of air speed was also incorporated. Based on these results, the Basic Scale of Effective Temperature was proposed, applicable to men stripped to the waist. Yagloglou & Miller (1925) shortly afterwards presented the Normal Scale of Effective Temperature applicable to men wearing light indoor clothing. The effective temperature for both scales was expressed as the temperature of still and saturated air, which the subjects judged to be as warm as any given combination of temperature, humidity, and air speed. Later, Bedford (1946) modified these scales by replacing the dry-bulb temperature readings with globe thermometer readings in order to incorporate the effect of radiant heat. Based on Bedford's corrected scales, Smith (1955) devised nomograms for both the basic and the normal scale, taking into account work-rate in addition to the physical parameters determining heat load. However, the Smithian nomograms are seldom referred to, and no investigation using them appears to have been made.

Although the Effective Temperature scales (ET-scales)

were based on assessment of thermal sensation, the Pittsburgh workers stated that the scales could also be used as valid measures of the physiological effect of heat exposure. Therefore the scales have been extensively used in experiments studying the effects of heat stress on physical and also on psychological performance. However, it has been found, particularly in physiological studies, that the scales do not correctly reflect the effects of humidity (Yaglou 1949, Smith 1955, Macpherson 1962). At low temperatures, these effects are over-estimated, whereas at high temperatures approaching the limits of tolerance, they are under-estimated. The effects attributed to air speed are also in error at high temperatures.

Because of these shortcomings and in order to construct a thermal index based on degree of physiological strain, Mc Ardle *et al.* (1947) devised the Predicted Four-Hour Sweat Rate—P4SR-scale. As the name implies, this index expresses the heat stress with reference to the amount of sweat secreted by the acclimatized young men Mc Ardle *et al.* exposed to different combinations of the four physical climate variables. Furthermore, this empirically obtained index also makes allowance for the heat stress caused by work-rate and clothing. The P4SR-scale thus takes account of the six most important factors that contribute to the individual thermal stress.

One disadvantage with the P4SR-index is that similar to the ET-scales, it is applicable to a restricted range of climates and in principle cannot be used for ambient temperatures below 27°C DB. According to Smith (1955), who compared the efficiency of the corrected ET-scales with the P4SR-scale in average predictions of the physiological strain displayed by Man, the P4SR-scale, under most conditions, is the more accurate index. However, both indices may be greatly in error in predicting the degree of physiological

strain for an individual. Löfstedt (1966) found that the P4SR-index was also more accurate than the theoretically derived and empirically determined index of Belding & Hatch (1955) in predicting average physiological strain. However, Löfstedt (1967) showed that if the relation between evaporation required to maintain thermal equilibrium and the maximum evaporation in a given climate is expressed as a linear difference, i.e. $E_{\max} - E_{\text{req}}$, instead of a quotient, as proposed for the original index, i.e. $\frac{E_{\text{req}}}{E_{\max}} \times 100$, a good linear correlation to physiological reactions is obtained.

Performance in heat as a function of exposure duration

In a review of the effects of high ambient temperature on mental performance, Wing (1965) called attention to an often neglected physical variable of the **experimental situation**; namely, exposure time. According to Wing, an inverse, exponential relation exists between heat exposure duration and the lowest temperature that yields significant impairment of mental performance. Thus a subject can tolerate about 30°C ET for four hours before his performance is adversely affected, whereas he cannot maintain his performance unimpaired for more than one hour when exposed to about 35°C ET. However, Wing emphasized that the relation is tentative, and therefore "it becomes especially important to assess what set of conditions the curve most adequately represents and to urge the reader not to generalize to conditions which it does not represent." When discussing these limiting conditions, Wing referred to a number of factors canvassed by other reviewers; some of these are treated below. A strongly limiting condition not discussed by Wing is that the time at which a task is performed and the exposure duration do not necessarily refer to the same period of time.

A task may be allotted during the first, second, or third hour of a three-hour study, or it may last throughout the whole exposure.

Comments: It should be noted that Wing's analysis and reasoning are restricted to the relation between time of exposure at a given environmental temperature and performance, ignoring partly the relation between stress and strain, i.e. between ambient temperature and body temperature, and partly the relation between body temperature or other measures of strain and performance.

As psychological functioning depends on physiological processes, it seems reasonable to suggest that the body temperature or the function of all the thermoregulatory system is crucial for maintained performance. When a subject is exposed to heat, performance changes occur because the heat affects the physiological activity of the body. A number of compensatory reactions, such as sweating and vasodilatation, are initiated. In order to accomplish the thermoregulation, the body is forced to redistribute its energy resources. The initial cost of adaptation is thus rather high, but it probably decreases as a state of thermal equilibrium is reached. Then no drastic reorganization of the thermoregulatory function is required. However, thermal equilibrium has been reached on a higher level of physiological activity.

According to this model, the compensatory thermoregulatory activities that occur rather early during heat exposure might cause an immediate change in performance. Because the cost of adaptation is supposed to decrease while the level of physiological activity is supposed to increase until a steady state of thermal equilibrium is reached, the total strain can be expected to remain rather constant.

Consequently, the performance will change slightly after the initial change.

In contrast to Wing's reasoning, which implies that performance deterioration under heat load is a function of progressively increasing thermal fatigue, the present hypothesis suggests that the detrimental effect of heat depends on a functional reorganization of the thermoregulatory system. The effects of this reorganization are supposed to appear already at the beginning of thermal exposure, and they do not increase progressively with exposure time. However, the two models do not preclude each other, and the changes in performance under heat load are most probably explainable in terms of a synthesis of the two models.

The interrelations between heat stress, strain, and performance

Besides the uncertainty about the relative importance of the physical determinants of heat stress, another difficulty in understanding Man's psychological reactions under thermal stress is that the functional relation between them and his physiological reactions, and them and the climate, is not yet fully understood. A linear relation between ambient temperature and performance is often assumed, implying that work-rate and efficiency deteriorate progressively as the environmental temperature increases. The possibility of a curvilinear relation is seldom considered nor is the possibility that not only the air temperature, humidity, and air speed, but probably also the body temperature and other strain variables determine psychological performance.

After reviewing some recent neurophysiological research, Provins (1966) proposed a hypothesis which

deals with both points. With reference to human skilled performance under thermal load, he suggested that "an increase in body temperature rather than a rise in the effective climatic temperature is the real source of heat stress." Furthermore, he suggested that increased body temperature influences the general level of arousal of the individual in such way that a slightly increased body temperature decreases the level of arousal and makes the individual feel drowsy and sleepy. A further increase in the body temperature is suggested to be arousing and to make the subject irritated and restless. Thus Provins proposed a U-shaped relation between body temperature and level of arousal. About the relation between level of arousal and performance, he referred to Hebb (1955) and Duffy (1957) emphasizing that both low and high levels of arousal are conducive to poor performance, i.e. performance shows an inverted U-shaped relation with arousal. However, Provins himself did not study to what extent curvilinear relations have been obtained in heat stress research between body temperature—or lacking such data, climatic temperature—and arousal, on one hand, and performance, on the other.

Concerning Provin's hypothesis of an U-shaped relation between body temperature and arousal, it is not generally agreed, as other researchers have suggested a linear relation instead of a curvilinear one. The Cambridge researchers have argued that environmental heat is arousing (Pepler 1959 a, Broadbent 1963, Poulton *et al.* 1974) whereas others have suggested that heat is monotonically de-arousing causing thermal fatigue (Bursill 1958).

In contradiction of Provins' hypothesis, some researchers failed to find any evidence that human skilled performance depends on body temperature. Pepler (1963) concluded in a comprehensive review of performance and well-being in heat that "no studies

have been reported as yet which establish a direct relationship between a deterioration of skilled performance in heat and an associated physiological state or process."

Mackworth (1950) found average curves indicating that performance decreased with increasing body temperature. However, after cross-tabulating his data analysing the relation for each climate condition separately, Mackworth concluded that the relation between performance and body temperature was non-causal, as both variables depended on the environmental temperature.

When Pepler wrote his review, no paper had yet appeared which primarily studied performance changes in relation to changes in body temperature. Therefore body temperature was not always adequately measured in a standardized way, and performance changes were mostly suggested to depend on room temperature, which was an independent and completely controlled variable. The relation between performance changes and body temperature was studied as a by-product, if analysed at all. During the past ten years, the technique of inducing controlled hyperthermia has been utilized for investigation of how raised body temperature influences mental performance. Some of these studies are reviewed below.

Intervening variables

The fact that different aspects of behaviour and performance are differently influenced by the same thermal stress has further complicated the results of heat stress research, although some reviewers (Provins & Bell 1962, Pepler 1963) have appreciated this and have analysed performance on mental and sensory-motor tasks separately: "the empirically

derived data are insufficient for a completely satisfactory classification of heat effects" (Bell & Provins 1962).

Besides the lack of classification categories of heat effects, the absence of any thermal effects on performance, even at the limit of tolerance, has been a complicating factor. Referring to Ryan's book on work and effort (Ryan 1947) Bell & Provins have repeatedly emphasized the importance of paying attention to the cost of performance in warm conditions. An unaffected performance under thermal stress does not necessarily indicate that heat does not influence the subject. To some extent, he can counteract a tendency to decrease performance output by being strongly motivated to work hard (Mackworth 1947) or by putting more effort in his work provided he has not already mobilized his resources to the utmost (Mackworth 1946). Probably because of the lack of reliable and valid methods for studying effort, few researchers have tried to measure reported or objectively registered reactions of effort. In an investigation by Pepler & Warner (1968), subjectively reported effort in mental work was studied and found to be associated with the environmental temperature. Using an electrophysiological technique proposed by Kalsbeek & Ettema (1965), Wyon (1969) reported in a study of the effects of moderate heat stress on the mental performance of children that sinus arrhythmia derived from ECG was significantly related to degree of intellectual effort.

It should be emphasized that not only features of the environment and the task but also characteristics of the heat exposed subject determine his heat induced performance changes. Several stress researchers (e.g. Mackworth 1950, Provins & Bell 1962, Pepler 1963, Broadbent 1963, Welford 1965, Wing 1965, Wyon 1970, Wilkinson 1974) have pointed out that psychological

characteristics, such as intelligence and personality, in addition to biological characteristics, such as age, sex, and heat acclimatization, act as intervening variables which mediate the effects of heat stress. Besides these attributes of the individual, which are invariable in the sense that they do not change as a function of the task or the experimental conditions, there are other variable characteristics of the subject, such as attention, concentration, arousal, and motivation. It is remarkable that few heat stress studies have paid attention to these individual characteristics, not least as they are of great concern when the physiological and psychological demands of special risk groups, such as children, old people or the sick, are to be considered.

The present review and its disposition

This review of studies of the effects of heat on human performance was made in two steps. The first was taken when planning the experimental study. Based on previous findings, the relevant questions of investigation were formulated and the theoretical model was outlined. The second was taken when the experimental data were obtained. It resulted in the presented classification of previous results and trends, and it served as the frame of reference within which the present findings were interpreted.

The review proposes to examine some seemingly contradictory results and conclusions in previous research; results and conclusions that could be brought to consonance in view of the proposed theoretical model, taking into account both environmental and individual variables, and in view of the obtained experimental findings. As the results of previous heat stress research have been

complicated by the fact that different aspects of performance are differently influenced by the same thermal stress, it was decided to analyse mental, perceptual and non-motor, and psycho-motor tasks separately.

Within this framework, studies reporting statistically significant and non-significant results were compared with respect to the factors that might explain the discrepant findings. Although statistical techniques for trend analysis were not used in the studies reporting significant results, the findings were reviewed with special attention to the occurrence of linear and curvilinear trends and to the functional relation between thermal load and performance.

A curvilinear trend was suggested for results displaying a non-monotonic function with the maximum (or minimum) value significantly different from lower (or higher) values. A linear trend was interpreted partly for results showing a monotonic function with significant differences between the observation values and partly for significant results showing a non-monotonic function, but without the maximum (or minimum) value being significantly different from lower (or higher) values.

In most reviewed studies, the heat stress was expressed as air or effective temperature. As there is no generally agreed measure of heat stress (although the ET-scale is the most commonly used index and some previous climate data cannot be expressed in any other form) and as the P4SR-scale seems to be one of the best heat stress indices, the environmental heat was expressed with both indices.

Besides studying the relation between heat and performance with reference to statistical functions, it was also examined with reference to physiological

functions. In studies reporting physiological data, the performance changes were related to physiological parameters and also to the environmental conditions.

Facts of the reviewed studies are reported in the initial part of each section below, and the conclusions to be drawn from the facts are presented in the final part of each section. A summarizing concluding section is presented at the end of the review. Figures 1 - 6 illustrate the occurrence of linear and curvilinear trends in the results. For studies reporting statistically significant results, the reliable minimum difference in effective temperature or body temperature between the optimum temperature and any other adverse temperature is presented in Tables 1 - 11. These tables, for studies reporting not significant results, also show the greatest temperature difference that causes no change in performance. Questions posed but not answered by the review are discussed at length under the heading: Problem analysis.

Mental tasks: linear trend

1. Givoni & Rim (1962)
2. Wing (1965)
3. Viteles & Smith (1946)
4. Wing & Touchstone (1965)
5. Pepler (1958)
6. Mackworth (1950)
7. Holmberg & Wyon (1969, 1972)
8. Wyon (1969)
9. Wilkinson *et al.* (1964)

Figure 1 a, b and Table 1 a present studies reporting a statistically significant deterioration of mental performance under heat load, interpreted as a linear trend.

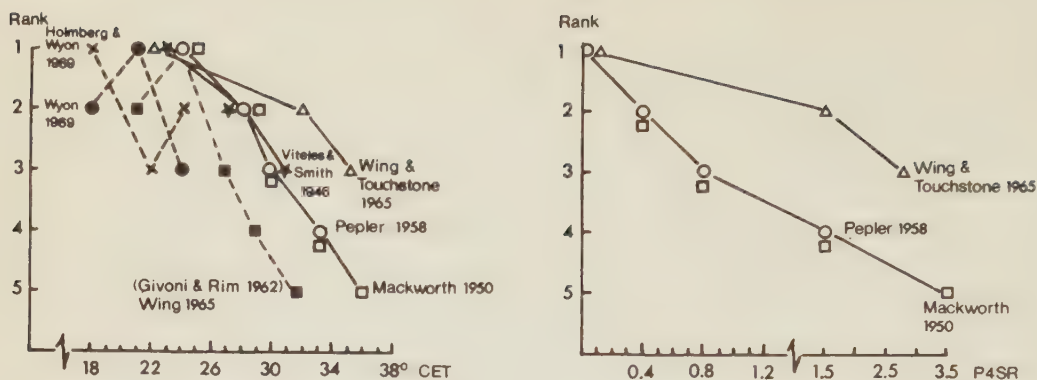


Figure 1. Linear trend between environmental heat—expressed in ET-units (1a) and P4SR-units (1b)—and mental performance (rank 1 denotes optimum performance).

1. Givoni & Rim (1962)

exposed four normally-dressed male subjects to no less than 17 different temperature conditions ranging between 21° and 32°C ET. During each 2-hour session, a mental multiplication task was set twice; the subjects also rated their thermal sensation and sensible perspiration. The two runs of the performance task were made during the second half of each hour. Oral temperature and weight loss were measured immediately after the exposure. Before the main experiment, the subjects were tested for intelligence and emotional stability at 25° and 43°C DB and 40% RH.

Similar to previous findings, the sweat rate (weight loss) data indicated that the ET-scale overestimated the effects of humidity. On the basis of a simple graphical analysis, Givoni & Rim concluded that "no clear relationship exists between performance and environmental stress, either in its physiological or subjective manifestations." Furthermore, it was

found that the scores on the tests of intelligence and of emotional stability remained constant irrespective of the climatic conditions.

Comments: Any heat induced changes of intelligence and emotional stability were probably not to be expected. Tests of these aspects are constructed to measure individual characteristics which are supposed not to change abruptly with changes in the environment. Unfortunately, Givoni & Rim did not study performance changes in relation to either oral temperature or personality factors.

2. Wing (1965)

reanalysed the Givoni & Rim study because it completely lacked statistical testing. He grouped the 17 test conditions into five intervals of effective temperature, represented approximately by the midpoints: 21° , 24° , 27° , 29° , and 32°C .

Corresponding P4SR-values cannot be stated.

Using non-parametric testing, Wing found a significant over-all effect of temperature. The number of completed items in both runs at the two highest effective temperatures were almost significantly fewer ($p < 0.062$ is the highest level of significance at which the null hypothesis can be rejected at one-tailed testing with a sample of four subjects) than the number completed at 24°C ET (Figure 1 a; Table 1).

Comments: Unfortunately, Wing did not report whether the performance at 24°C ET was also better than at 21°C ET . Probably it was not; therefore the trend was interpreted as linear, although it seems to be curvilinear in Figure 1 a. Furthermore, it is noteworthy although Wing himself did not discuss it—that in opposition to his suggested interrelations between heat stress, exposure duration, and performance—discussed at length above under the heading

Performance in heat as a function of exposure duration—the number of completed items was approximately the same in both runs, i.e. after one hour and after two hours of heat exposure.

3. Viteles & Smith (1946)

investigated the effect of change in atmospheric conditions and noise on the performance of six navy candidates, 18-21 years old and of at least average intelligence. Four conditions— 23° , 27° , 31° , and 34°C normal effective temperature—were studied in combination with three levels of noise: 72, 80, and 90 dB. No data were given about the subjects' clothing; therefore the heat stress cannot be expressed by means of the P4SR-scale. In four sessions before the main experiment, the subjects were acclimatized and trained on the seven experimental performance tasks (mental tasks: multiplication, letter coding; perceptual and non-motor tasks: number checking, dot localization, maze tracing; perceptual and motor tasks: tracking, serial choice) for two hours at 72 dB and 23° , 23° , 27° , and 31°C ET, respectively.

The main experiment consisted of 42 4-hour experimental sessions, scheduled six days a week for seven weeks. As only performance data from series II—with three weeks of experimental work periods at 72 dB and 23° , 27° , and 31°C ET—were statistically analysed, the review is restricted to this part of the study. The order of the tasks was counterbalanced across the experimental series; thus the time at which the tasks were given cannot be unequivocally stated. Each task was carried out for half an hour at each session; except tracking, which was carried out for one hour. Three different criteria were used to express the performance: a) output, b) error score, and c) variability score. In order to motivate the subjects, base and bonus payments were made.

Viteles & Smith found that oral temperature and pulse rate were increased when the subjects were exposed to heat:

a) The oral temperature increase was about 0.8°C at 31°C ET, and about 1.3°C at 34°C ET, a condition that no subject could tolerate for four hours at the first exposure and only four could tolerate for the full period at the second exposure.

b) The pulse rate increased approximately 20 beats/min at 31°C ET and 45 beats/min at 34°C ET.

In the mental multiplication test, the output was decreased at 31°C ET (96.7%) compared with 23° (100%) and 27°C ET (99.1%), whereas the two lowest temperatures did not differ to a statistically significant extent (Figure 1 a; Table 1).

Comments: It should be noted that the performance changes were not analysed with respect to the degree of physiological strain, nor were they related to the intelligence or the initial performance data available for each subject.—The results referring to the other tasks are given below.

4. Wing & Touchstone (1965)

also reported statistically significant results which indicated a linear relation between heat stress and performance. For one hour on three successive days, they exposed three groups of five young male students to 22° , 32° , and 35°C ET in counterbalanced order. The volunteers were dressed in T-shirt, shorts, and shower-clogs, and it is therefore possible to estimate the corresponding P4SR-values, which would be approximately 0, 1.5, and 2.8, respectively. At each exposure, the short-term memory was tested in five successive recall trials by means of a set of six aurally presented word-lists of different difficulty. No physiological data were recorded.

A graphical analysis indicated that, apart from the difficulty of the test material, a systematic reduction in the number of words correctly recalled was noted with an increase in temperature (Figure 1 a, b). The statistical analysis showed that the performance at the most stressing climate—35°C ET or 2.8 P4SR—was different from the performance at the other two climates, which did not differ (Table 1). However, Wing & Touchstone remarked that "about a quarter of the subjects either were not affected by high temperatures, or were able to compensate for the thermal stress, or else were poorly motivated under the lowest, control temperature," as they showed little change in performance.

Moreover, it was found that the learning at each exposure from trial to trial was approximately the same under all temperature conditions.

5. Pepler (1958)

reported a series of experiments, in the tropics. In a climate chamber, he exposed naturally acclimatized young men to different temperature conditions while they were engaged in mental, perceptual-but-not-motor, or psycho-motor work. The subjects wore shorts and sandals and, as almost all environmental variables and work rates were given, the heat stress can be expressed either by means of ET- or P4SR-values. Before and after each exposure, the subjects were weighed nude, and their rectal temperatures were recorded.

In one of his experiments, Pepler studied high-speed decision taking by means of a paced task. On a moving loop, a series of 20 symbol cards were irregularly spaced and presented at high, medium, and low speed. The subjects had to compare the six symbols on each card with the symbols on ten stationary cards and report the number of differences between them. The

performance was measured by the number of missed signals and error percentage. Four temperature conditions 24° , 27° , 30° , and 33°C ET, corresponding to approximately <0 , 0.4, 0.8, and 1.4 P4SR, were each presented for about 80 minutes to 24 subjects in a repeated measure latin square design.

At the fastest speed of presentation, the error percentage increased linearly with the thermal stress, and the performance was different between climates differing at least 5°C (Figure 1 a, b; Table 1). There were no statistically significant results at medium or low presentation speeds (Table 4).

Comments: Because Pepler analysed each speed of presentation separately, no information was given about interaction effects. Nor was information given about the relation between rectal temperature and performance. The rest of the experiments are presented below.

6. Mackworth (1950)

studied mental performance using a coding test consisting of a form-board and a set of small flat squares that had to be arranged on the board according to coded instructions. Twelve fit young men wearing shorts were exposed twice to each of five different heat stress conditions: 24° , 27° , 30° , 33° , and 36°C ET or approximately 0, 0.4, 0.8, 1.4, and 3.5 P4SR units. The exposure time was three hours. For two to three weeks before the main experiment, the subjects were artificially acclimatized three hours a day to effective temperatures ranging from 31° to 36°C . They had also practised on the coding test for about one hour a day for a fortnight in order to eliminate learning-how-to-learn effects.

Mackworth found that the error score increased logarithmically with the ambient temperature according to the formula

log performance = $1.2136 + 0.0803^{\circ}\text{F}$ (dry bulb).
 The increase in error score was statistically significant when the effective temperature was raised to 30°C or above compared with the performance at the two less stressful conditions (Figure 1 a, b; Table 1).

Mackworth plotted error scores against rectal temperature and found "a definite rising trend for the average incidence of errors as the rectal temperatures rose." Although he considered the relation to be non-causal, he concluded: "it looks safe to say that if a group of twelve to twenty acclimatized men have been working indoors at a sedentary task for two or three hours, and if their average rectal temperature is found to be more than $100^{\circ}\text{F}^{1)}$, then on the whole that group of men is not likely to have been working at full efficiency, given that they are dressed as in these experiments."

7. Holmberg & Wyon (1969)

studying the dependence of performance in school on classroom temperature, presented results of a less straightforward linear trend for performance means than that found in previously reviewed studies (Figure 1 a). In a repeated measure design, three classes of fifty 8-9 year-old children were exposed to air temperatures of 20° , 27° , and 30°C for 80 minutes in an observation classroom. Eighty children in four classes were similarly exposed to air temperatures of 20° and 30°C . As the air speed was always less than 0.05 m/sec, and the relative humidity (RH) ranged between 30% and 40%, the normal effective temperatures of the three conditions would be approximately 18° , 22° , and 25°C , and the corresponding P4SR-values <0 , 0, and 0.4. Intelligence

1) $100^{\circ}\text{F} = 37.8^{\circ}\text{C}$

data was available for each child but was not utilized in the performed analyses.

For the younger children significant over-all temperature effects were noted on a reading test and an opposites test (Figure 1 a; Table 1). Reading speed and comprehension were both worse—about 30%—at the two highest temperatures than at 18°C ET. But the difference between the two warmest climates was not statistically significant. In the opposites test, the only statistically significant difference also occurred between 18°C and 22°C ET.

Statistically significant and linear changes in posture, clothing, and appearance were found for the younger children with increasing air temperatures (Holmberg & Wyon 1972). An index of perceptible response to heat was formed on the basis of posture, clothing, and appearance. For this index, a statistically significant over-all effect of heat was found. The value of the index was higher at 22°C ET than at 18°C ET, and lower than that obtained at 25°C ET, i.e. thermal load and index of perceptible response to heat were definitely linearly associated.

8. Wyon (1969)

on the pretext of studying the effects of noise on mental performance exposed, in groups of four, 48 normally dressed 11-year old boys to one of three temperatures: 20°C, 23.5°C, and 27°C DB, with an air speed of 0.1 m/sec. Half of them worked in a "quiet" environment (65-70 dB), the other half in "noise" ranging between 85 and 90 dB. Provided the relative humidity, reported "normal" for the summer season, was approximately 50%, the normal effective temperatures would be 18°C, 21°C, and 24°C, whereas the P4SR-value for all conditions would be less than zero. During the two hours of heat exposure, the subjects were given five different performance tasks (mental

tasks: creativity, addition, reading, concept attainment; perceptual and non-motor task: cue-utilization) without any time restrictions.

Wyon reported a significant over-all temperature effect on the number of repeats in a creativity test that measured divergent thinking. However, no trend analysis was performed. Although the trend for the performance means seemed to be quadratic as Figure 1 a shows, the relation between heat stress and performance was considered linear, as only the difference between 21° and 24°C ET, but not between 18° and 21°C ET, was statistically significant. Moreover, the difference between the highest and the lowest temperature was significant too.

The rest of the tasks in this experiment are reviewed below.

9. Wilkinson *et al.* (1964)

performed an investigation which differs from the others in that body temperature was the independent and controlled variable instead of air temperature. First, twelve fit army volunteers, 22-23 years old, were, at four sessions at normal body temperature, trained on three performance tasks: a) auditory vigilance, b) addition, and c) serial choice. Then followed four replicate periods of four consecutive days of performance testing, so scheduled that, on the first three days of each period, the subjects were tested at raised body temperatures: 37.3°, 37.9°, and 38.5°C; on the fourth day, they were tested at normal body temperature. This design permitted Wilkinson *et al.* to study also the effects of acclimatization on performance. As 21 minutes were devoted to each task, and the changeover between tasks took 3 minutes, and the subjects were given a 21-minute rest between the last two tests—addition and serial choice—the total time of performance testing under heat load was about 90 minutes.

Controlled hyperthermia was achieved by first exposing the subjects naked to 43°C DB, 100% RH, and 0.25 m/sec air speed until the prescribed level of body temperature was reached. Thereafter they were dressed in a thin vapour-barrier suit and tested for performance at a room temperature of 37°C and a relative humidity of the air of 20%. In order to maintain a constant body temperature, the suit was ventilated with air of 35°C DB and 20°C wet bulb (WB). The subjects were strongly motivated by monetary rewards for performance.

Concerning the subjects' physiological reactions, it was found that the sweat rate rose to approximately twice as large at 38.5°C body temperature as it was at 37.3°C . The sweat loss did not appear to be linearly related to the body temperature, as 0.6°C increase of body temperature from 37.3° to 37.9°C produced a much larger change in sweat loss than raising the body temperature from 37.9° to 38.5°C . Furthermore, during the experimental period, the sweat rate increased progressively for a given level of body temperature and had more than doubled by the end of the programme.

In contrast to the findings and conclusions presented by Mackworth (1950), Wilkinson *et al.*, noted a causal and statistically significant relation between performance and body temperature. The performance on the addition test deteriorated with increasing body temperature (cf. a negative relation between auditory vigilance and body temperature reported below under the heading Perceptual and non-motor tasks: linear trend). At 38.5°C body temperature, the number of items completed was less than at normal body temperature— 36.5°C —whereas the number of errors was higher (Table 1). The Spearman rank correlation was for sums done $r_s = -.54^*$ and for errors $r_s = -.75^{***}$. As indicated by these coefficients,

the monotonic trend was more pronounced for accuracy than for speed. In fact, the means for sums done formed a curvilinear trend, but as the performance at the optimum level of body temperature —37.3°C—was not reported to be statistically different from the performance at either normal or 38.5°C body temperature, the relation is considered approximately linear. (It is emphasized that no favourable effect of acclimatization on performance was revealed.)

Mental tasks	°C ET
Multiplication (output)	
(Givoni & Rim 1962) Wing 1965	5:24-29
Viteles & Smith 1946	4:27-31
Short term word memory	
Wing & Touchstone 1965	3:32-35
Decision taking (error score; fast speed)	6:24-30
Pepler 1958	27-33
Coding (error score)	
Mackworth 1950	3:27-30
Reading speed	
Holmberg & Wyon 1969: exp 1	4:18-22
Reading comprehension	
Holmberg & Wyon 1969: exp 1	4:18-22
Opposites	
Holmberg & Wyon 1969: exp 1	4:18-22
Creativity (repeat score)	
Wyon 1969*	3:21-24
Addition (output)	
Wilkinson <u>et al.</u> 1964	<u>2:36.5-38.5</u>
Addition (error score)	
Wilkinson <u>et al.</u> 1964	<u>2:36.5-38.5</u>

Table 1. Studies of mental performance under heat stress yielding statistically significant results ($p < .005$) interpreted to indicate a linear relation between heat stress and mental performance. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature; underlined values refer to body temperature; asterisk (*) denotes experiments on interaction between heat and other stresses.

Conclusions: Apart from the study by Givoni & Rim the first five experiments definitely show a monotonic decrease in performance with an increase in environmental heat. Therefore it can be concluded that an average effective temperature of about 27°C or lower probably does not significantly impair mental performance. If the effective temperature is raised on average 4° to about 31°C ET, it can be expected that the deterioration of the mental performance of the type reviewed will be statistically significant. The critical zone between 27°C and 31°C ET agrees completely with the conclusion reached by Mackworth (1950) on the basis of a comprehensive series of heat stress studies.

If, to the previously-mentioned five studies, those of Holmberg & Wyon (1969) and Wyon (1969) are added the critical zone is found to be decreased to 23°C - 27°C ET, i.e. statistically significant adverse performance changes can be expected to occur at about 27°C ET. The effects of the extraordinarily low temperatures on the subjects in these studies might be explained by two facts, which make these investigations differ from the others:

- a) The subjects were school children of both sexes.
- b) They were heat exposed in groups without knowing that they were attending a heat experiment.

According to Wilkinson *et al.*, a causal relation exists between mental performance and degree of physiological strain, implying that the performance is significantly impaired at 38.5°C body temperature. The study by Viteles & Smith suggested that a reduction in performance might arise when the body temperature is raised 0.8°C . This figure is consistent with Mackworth's results, which indicate that, on average, the mental performance of a group of men dressed in shorts will be impaired when their average rectal temperature exceeds 37.8°C .

Mental tasks: curvilinear trend

1. Pepler & Warner (1968)
2. Pepler (1958)

A tentative curvilinear trend was derived from the results of only two studies.

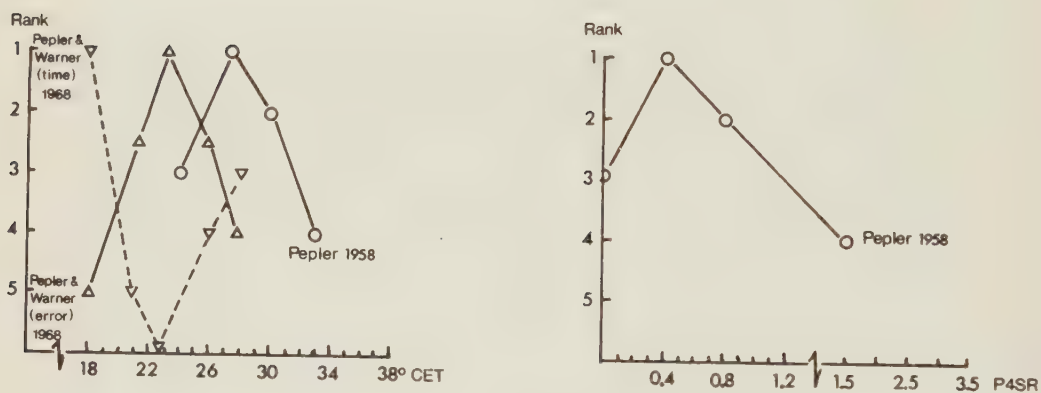


Figure 2. Curvilinear trend between environmental heat—expressed in ET-units (2a) and P4SR-units (2b)—and mental performance (rank 1 denotes optimum performance).

1. Pepler & Warner (1968)

studied the effects of temperature on learning. At Kansas State University in the late autumn, they administered a programmed text to 36 male and 36 female students dressed in cotton twill uniforms and socks. Four aspects of learning performance were scored: a) error and, b) work rate per three min period; c) error percentage, and d) time taken to complete assignments (number of three min periods worked). In groups of 12, the subjects were exposed three hours a day for six consecutive weeks to six different air temperatures, approximately 17°, 20°, 23°, 27°, 30°, and 33°.

30, and 33°C, relative humidity 45%, and air speed 0.15 m/sec. Thus the normal effective temperatures would be 15°, 18°, 20.5°, 23°, 25.5°, and 28°C. The P4SR-values for the three coolest climates would be less than zero, whereas the others would be approximately 0.1, 0.4, and 0.8 P4SR. The programmed text was given during the final two hours of each session, and the subjects worked at their own pace.

A tentative inverted U-shaped relation was found between error rate and room temperature (Figure 2 a). The subjects made less errors at 23°C ET (0.1 P4SR) than at any other condition. The error rate at this temperature was statistically significant and differed from the error rate at 15°C and 18°C ET, whereas the difference at 28°C ET approached significance (Table 2). At 23°C ET, the subjects also experienced less effort than they did when working at 15°, 25.5°, or 28°C ET. This might have been because the students worked more rapidly above and below the optimum level—23°C ET—noted with respect to error rate. However, only the differences between this and the two coolest climates—15° and 18°C ET—were statistically significant, whereas the difference between 23° and 28°C ET approached statistical significance (Figure 2 a; Table 2). No interaction was found between either of the two affected performance measures, on one hand, and sex or academic ability, on the other. (In a symposium discussion accompanying the report, Pepler stated that "optimum temperature for learning was approximately 78 degs"; this corresponds to 25.6°C DB.)

Comments: Although Pepler himself did not comment on this, it is possible that the optimum temperature for learning was probably the one most resembling the normal indoor climate at Kansas during the summer and autumn. Thus the optimum level for performance

approximately corresponded to the adaptation level (Helson 1964) of the subjects with respect to room temperature.

The results with respect to error rate and the time taken to complete the assignments do not completely meet the demands to be interpreted as showing a curvilinear trend. Therefore they should have been reported above under the heading Mental tasks: linear trend. However, as Figure 2 a shows, the means for the six climates reflected a consistent curvilinear trend, and the tests of significance approached significance. Pepler & Warner also considered the relation between learning and ambient temperature to be curvilinear.

2. Pepler (1958),
in the study of high speed decision taking reviewed above (Mental tasks: linear trend), reported a statistically significant temperature effect for the slowest speed of presentation (Table 2). An inverted U-shaped relation appeared between number of decisions the subjects failed to make and effective temperature (Figure 2 a, b).

Pepler concluded that "the least number of comparisons were missed in the moderately warm climate with an effective temperature of 81°F , and more in both the cooler and warmer climates." He considered this condition— 27°C ET or approximately 0.4 P4SR—to be similar to the normal indoor climate at Singapore.— Thus the optimum temperature again corresponded to the assumed adaptation level of the subjects.

Comments: The report of the results of the significance testing did not make it quite clear whether the optimum temperature, 27°C ET, differed significantly from both lower and higher temperatures. However, as a tentative curvilinear trend appeared at all

presentation speeds, the significant results reported for the low presentation speed were interpreted to form a curvilinear trend as shown in Figures 2 a and b.

Mental tasks	°C ET
Programmed learning (error rate)	
Pepler & Warner 1968	5:23-18
Programmed learning (time score)	
Pepler & Warner 1968	5:23-18
Decision taking (omissions; slow speed)	3:27-24
Pepler 1958	27-30

Table 2. Studies of mental performance under heat stress yielding statistically significant results ($p < .005$) interpreted to indicate a curvilinear relation between heat stress and mental performance. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature.

Conclusions: Only two studies have been reviewed, and the curvilinear trends appearing must be considered tentative; therefore no firm conclusions are to be drawn with respect to whether there really is a curvilinear relation between heat stress and mental performance. Actually, the results would have been interpreted as a linear trend if the criteria for trend classification had been strictly adhered to.

Apart from how the trends are to be classified, the results can be understood to indicate that the mental performance with respect to learning efficiency and decision taking will probably be impaired when the ambient temperature exceeds 27°C ET. This conclusion

is consistent with the one presented above for mental tasks displaying a linear trend. Furthermore, the optimum temperature for decision taking and accuracy in learning apparently coincides with the habitual ambient temperature of the subject.

Mental tasks: significant results: no trend

1. Chiles *et al.* (1972)
2. Ryd (1970)
3. Holmberg & Wyon (1969)
4. Trygg (1972; Bliding *et al.* 1966)
5. Wyon *et al.* (1973)

For the studies to be reviewed next, it was impossible to analyse the form of the heat stress - performance relation, as only two temperatures were studied. Table 3 summarizes the results.

Mental tasks	°C ET
Multiplication (output)	
Chiles <i>et al.</i> 1972*	17:19-36
Ryd 1970	1:20-21
Reading speed	
Holmberg & Wyon 1969:exp 1	7:18-25
Reading comprehension	
Holmberg & Wyon 1969:exp 2	7:18-25
Addition & memory (output)	
Trygg 1972:exp 2	38.0
Addition & memory (omissions)	38.0
Trygg 1972:exp 2	38.0

Table 3. Studies of mental performance under heat stress yielding statistically significant results ($p < 0.05$) without indicating any trend in the findings. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature; asterisk (*) denotes experiments on interaction between heat and other stresses; underlined values refer to body temperature.

1930 1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071 2072 2073 2074 2075 2076 2077 2078 2079 2080 2081 2082 2083 2084 2085 2086 2087 2088 2089 2090 2091 2092 2093 2094 2095 2096 2097 2098 2099 2100 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114 2115 2116 2117 2118 2119 2120 2121 2122 2123 2124 2125 2126 2127 2128 2129 2130 2131 2132 2133 2134 2135 2136 2137 2138 2139 2140 2141 2142 2143 2144 2145 2146 2147 2148 2149 2150 2151 2152 2153 2154 2155 2156 2157 2158 2159 2160 2161 2162 2163 2164 2165 2166 2167 2168 2169 2170 2171 2172 2173 2174 2175 2176 2177 2178 2179 2180 2181 2182 2183 2184 2185 2186 2187 2188 2189 2190 2191 2192 2193 2194 2195 2196 2197 2198 2199 2200 2201 2202 2203 2204 2205 2206 2207 2208 2209 2210 2211 2212 2213 2214 2215 2216 2217 2218 2219 2220 2221 2222 2223 2224 2225 2226 2227 2228 2229 2230 2231 2232 2233 2234 2235 2236 2237 2238 2239 2240 2241 2242 2243 2244 2245 2246 2247 2248 2249 2250 2251 2252 2253 2254 2255 2256 2257 2258 2259 2260 2261 2262 2263 2264 2265 2266 2267 2268 2269 2270 2271 2272 2273 2274 2275 2276 2277 2278 2279 2280 2281 2282 2283 2284 2285 2286 2287 2288 2289 2290 2291 2292 2293 2294 2295 2296 2297 2298 2299 2300 2301 2302 2303 2304 2305 2306 2307 2308 2309 2310 2311 2312 2313 2314 2315 2316 2317 2318 2319 2320 2321 2322 2323 2324 2325 2326 2327 2328 2329 2330 2331 2332 2333 2334 2335 2336 2337 2338 2339 2340 2341 2342 2343 2344 2345 2346 2347 2348 2349 2350 2351 2352 2353 2354 2355 2356 2357 2358 2359 2360 2361 2362 2363 2364 2365 2366 2367 2368 2369 2370 2371 2372 2373 2374 2375 2376 2377 2378 2379 2380 2381 2382 2383 2384 2385 2386 2387 2388 2389 2390 2391 2392 2393 2394 2395 2396 2397 2398 2399 2400 2401 2402 2403 2404 2405 2406 2407 2408 2409 2410 2411 2412 2413 2414 2415 2416 2417 2418 2419 2420 2421 2422 2423 2424 2425 2426 2427 2428 2429 2430 2431 2432 2433 2434 2435 2436 2437 2438 2439 2440 2441 2442 2443 2444 2445 2446 2447 2448 2449 2450 2451 2452 2453 2454 2455 2456 2457 2458 2459 2460 2461 2462 2463 2464 2465 2466 2467 2468 2469 2470 2471 2472 2473 2474 2475 2476 2477 2478 2479 2480 2481 2482 2483 2484 2485 2486 2487 2488 2489 2490 2491 2492 2493 2494 2495 2496 2497 2498 2499 2500 2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516 2517 2518 2519 2520 2521 2522 2523 2524 2525 2526 2527 2528 2529 2530 2531 2532 2533 2534 2535 2536 2537 2538 2539 2540 2541 2542 2543 2544 2545 2546 2547 2548 2549 2550 2551 2552 2553 2554 2555 2556 2557 2558 2559 2560 2561 2562 2563 2564 2565 2566 2567 2568 2569 2570 2571 2572 2573 2574 2575 2576 2577 2578 2579 2580 2581 2582 2583 2584 2585 2586 2587 2588 2589 2590 2591 2592 2593 2594 2595 2596 2597 2598 2599 2600 2601 2602 2603 2604 2605 2606 2607 2608 2609 2610 2611 2612 2613 2614 2615 2616 2617 2618 2619 2620 2621 2622 2623 2624 2625 2626 2627 2628 2629 2630 2631 2632 2633 2634 2635 2636 2637 2638 2639 2640 2641 2642 2643 2644 2645 2646 2647 2648 2649 2650 2651 2652 2653 2654 2655 2656 2657 2658 2659 2660 2661 2662 2663 2664 2665 2666 2667 2668 2669 2670 2671 2672 2673 2674 2675 2676 2677 2678 2679 2680 2681 2682 2683 2684 2685 2686 2687 2688 2689 2690 2691 2692 2693 2694 2695 2696 2697 2698 2699 2700 2701 2702 2703 2704 2705 2706 2707 2708 2709 2710 2711 2712 2713 2714 2715 2716 2717 2718 2719 2720 2721 2722 2723 2724 2725 2726 2727 2728 2729 2730 2731 2732 2733 2734 2735 2736 2737 2738 2739 2740 2741 2742 2743 2744 2745 2746 2747 2748 2

Investigating the effects of the combination of altitude (24°C DB, 44 RH, 447 mm Hg altitude) and temperature (36°C DB, 12% RH, 726 mm Hg altitude) using 24°C DB, 44% RH, 726 mm Hg altitude as reference condition. The effective temperature of the two conditions would be 13°C and 36°C respectively, but P45k-values cannot be stated, as both conditions are outside the range of the P45k-scale, i.e. less than -0.25 and greater than 6 P45k. Nine pilots, 30-46 years old, dressed in short-sleeved loose shirt, trousers, socks, and shoes were exposed to all three test conditions in counterbalanced order. Each exposure was scheduled according to a standardized procedure: 15 minutes change from reference to test condition, 60 minutes constant test condition, 15 minutes change from test to reference condition, and finally 15 minutes at the reference condition; a total of 75 minutes. During all the exposures, the subjects worked on each of the primary tasks, tracking and multi-location, and three secondary monitoring tasks. Before the main experiments, the subjects were given three training sessions of the performance tasks in the reference condition. Heart rate and rectal and skin temperature were the physiological measures recorded during the main experiment.

The increase in all physiological measures was statistically significant at 36°C ET, but not in the alternate condition. However, the physiological heat response did not appear until the last 11 minutes of each day, and rectal temperature first reached peak value—37.4°C—during the final 11 minutes in the reference condition.

The only statistically significant effect on the multiplication rate occurred for the "resource time" in the "temperature plus altitude condition", the

mean "response time" on the multiplication task increased from the first 15 minutes to the final 15 minutes, and the "response time" then remained almost unchanged during the 15 minutes when the chamber returned to the reference condition (Table 3).

Comments: As Chiles *et al.* did not study the relation between degree of physiological strain and performance, it cannot be concluded that the change of "response time" depended on the increased rectal temperature, particularly as the effect did not appear in the temperature condition, and in the temperature plus altitude condition, the effect occurred before the rectal temperature had reached its peak value. However, it seems as though a rising body temperature due to thermal load, under the added stress of anoxia, can adversely affect mental performance. The results for the other tasks are reported below.

2. Ryd (1969)
using 23°C DB as reference temperature also studied mental multiplication, but in contrast to Chiles *et al.* under "moderate" heat stress. In counterbalanced order, two school classes in the fifth year course were exposed in ordinary classrooms to 25°C DB and two other parallel classes were exposed to 27°C DB. The exposure time was about 45 minutes and the multiplication test was administered during the last 30 minutes together with some other tests (not reported in full). The relative humidity was said to range between 23% and 53% and in most cases was 30-40%, while the air speed was $\leq$ 0.1 m/sec. Thus the normal effective temperatures would be approximately 20°, 21°, and 22°C. For all temperatures, the P4SR-value would be less than zero; therefore none of the conditions could be considered to cause physiological heat strain.

One-tailed testing indicated a statistically

significant performance decrement—less number of correct answers—at 21°C ET, but surprisingly not at 22°C ET compared with the reference condition (Table 3). This temperature difference—1°C ET—is the least ever reported in all the reviewed studies causing impaired performance.

Moreover, it was found that, in one of the classes exposed to 21°C ET, "the less able section of the class" (identified from other tests) tried to solve significantly fewer items than they did at 20°C ET, but such a trend did not appear for the more able section. Also, in one of the classes exposed to 22°C ET, the error percentage increased significantly for the less able subjects, whereas it decreased significantly for the more able ones. According to Ryd, who used a doubtful statistical analysis, "a significant reduction both in the number of correct answers and in the number of answers submitted, and a significant increase in the percentage of mistakes" appeared for the less able children "when the results from the four groups are assessed jointly."

Comments: It is emphasized that the number of subjects varied from analysis to analysis without any explanation.

3. Holmberg & Wyon (1969)

in the previously reviewed study (see above, Mental tasks: linear trend) reported for the 11-12-year-old children, as they did for the younger children, significantly impaired performance on the reading test under heat load. At 25°C ET—0.4 P4SR—both reading speed and reading comprehension were worse than at the reference condition 18°C ET—≤0 P4SR (Table 3). Concerning the temperature effect, it was found that this was more marked in the afternoon, and the interaction between temperature and time of day was statistically significant.

4. Trygg (1972)

studied complex mental performance for different personality groups under controlled hyperthermia. In one of his studies—investigation 2—he exposed twentyfive 19-26-year old female students to three different thermal conditions. The subjects met the reference condition— 30°C DB—at the first session and at the second session were initially exposed to 50°C DB until the cranial temperature reached 38°C , whereupon the room temperature was regulated to achieve a constant hyperthermia, i.e. body temperature instead of room temperature acted as independent variable. However, during the last 30 minutes of the four hours exposure the chamber temperature was increased $3\text{--}5^{\circ}\text{C}$, causing the cranial temperature to rise $0.2\text{--}0.5^{\circ}\text{C}$. At the third session, the subjects during the exposure were exposed to that room temperature which had been previously required to maintain the cranial temperature at 38°C . A control group of 13 subjects was exposed three times to the reference condition. Before the heat experiment, the subjects were tested for memory span, speed of addition, personality, and physical working capacity. After 15 minutes of heat exposure, a combined memory and addition test was given, and the subjects worked on this for 120 minutes at the first and third trial and for 225 minutes at the second trial.

Trygg reported that the experimental group performed worse—fewer answers correct and more items omitted—than the control group at the second and third trial, when the subjects were approaching or had reached a cranial temperature averaging 38°C (Table 3). When different subjects reached this prescribed cranial temperature level, the chamber temperature could vary up to 10°C . The performance difference between the two groups was due to the experimental group deteriorating and the control group improving. However, this effect was not consistent in the

experimental group, as the least able subjects improved their performance in contrast to deteriorating average and most able subjects (cf. Ryd 1970).

It was found that change of performance was associated with two variables:

a) Body temperature. A relation was found between change of performance and change of cranial temperature ($r_s = .43^{\times}$), whereas physical working capacity was not associated with performance change.

b) Personality classification. Compulsive¹⁾ subjects tended to be most adversely affected. Dissociative¹⁾ subjects, concerning pulse rate, cranial temperature, and heat rating, showed greater instability than other subjects.

The importance of personality characteristics for heat induced performance change confirmed a previous result by Trygg, implying that the prerequisites for performance impairment on the combined addition and memory test were upset by thermal equilibrium in combination with a primitive and hysteroid personality (investigation 1: Bliding *et al.* 1966). Moreover, it was found in the Bliding *et al.* study that the dissociative subjects were characterized by an inability to adapt to the thermal and task load imposed on them, as revealed by high pulse rates throughout the heat exposure.

All studies reviewed so far were carried out under almost constant climate conditions. However, during recent years, a few studies were published concerning the effects of ambient temperature swings on the thermoregulatory system and performance.

1) This concept is explained below. See Psychological methods for measurement of ability, personality, and other individual characteristics.

5. Wyon *et al.* (1973)

exposed eight male and eight female students, 21-28 years old, wearing a standard uniform to a preferred room temperature determined in a preliminary exposure, and ranging between 23° and 27° with a mean of 26°C DB. The room temperature varied around the individually preferred value according to the following alternatives: 2° and 4°C in 8-minute cycles; 2°, 6°, and 8°C in 16-minute cycles; 4° and 8°C in 32-minute cycles. The conditions were repeated three times and were presented consecutively in a latin square design. The total exposure time, 7 hours 48 minutes, was divided on two separate runs. During the exposure, the subjects were free to work on an addition task, but they were paid a bonus for work done correctly.

The number of items attempted was greater with large room temperature swings (4° and 8°C) under long cycles (16 and 32 min) than with small and fast temperature swings (2° and 8 min, respectively). However, according to a parametric analysis of variance, no experimental condition differed to a reliable extent from the control condition with constant temperature. On the other hand, the accuracy of addition was greatest at constant temperature and declined with an increase in the temperature swing. This might be because the subjects rated large and slow temperature swings more uncomfortable than constant temperature. The subjects' assessments of arousal, fatigue, and freshness of the air were not influenced by the environmental conditions. Wyon *et al.* thus concluded: "Large ambient temperature swings appear to have a stimulating effect that is to be preferred to the apparently opposite effect of small temperature swings, but a constant, optimally comfortable temperature, where this can be achieved, would still seem to be preferable to either."

Conclusions: As the studies reviewed in this section

investigated only two temperatures, no valid conclusion can be drawn with respect to the trend-relation between environmental heat and mental performance. However, the results in the studies do not invalidate the conclusions presented under the heading Mental tasks: linear trend, i.e. mental performance runs the risk of becoming impaired above 27°C ET. The exception to this conclusion was once again found for a study in which school children were heat exposed in groups and not singly.

The study by Trygg on the effects of induced hyperthermia confirmed the conclusion of Wilkinson *et al.* that there is a functional relation between body temperature—at least above 38°C—and mental performance. According to Wyon *et al.* a constant and most comfortable indoor climate is to be preferred to varying environmental warmth.

Mental tasks: not statistically significant results

1. Holmberg & Wyon (1969)
2. Wyon (1969)
3. Viteles & Smith (1946)
4. Chiles *et al.* (1972)
5. Trygg (1972)
6. Wyon (1970)
7. Pepler & Warner (1968)
8. Griffiths & Boyce (1971)
9. Pepler (1958)
10. Chiles (1958)
11. Bartlett & Gronow (1953)

In several studies of the effects of heat on arithmetical work, no statistically significant effects have been reported. Table 4 lists the largest not statistically significant effective temperature

difference between the optimum temperature and any other adverse temperature in these studies. Design and procedure have previously been reviewed and only the relevant results are reported below.

Mental tasks	°C ET
Multiplication (output)	
Holmberg & Wyon 1969:exp 1	7:18-25
Holmberg & Wyon 1969:exp 2	7:18-25
Chiles <u>et al.</u> 1972	17:19-36
Multiplication (error score)	
Viteles & Smith 1946	8:23-31
Chiles <u>et al.</u> 1972	17:19-36
Chiles <u>et al.</u> 1972*	17:19-36
Multiplication (variability score)	
Viteles & Smith 1946	8:23-31
Addition (output)	
Wyon 1969*	6:18-24
Holmberg & Wyon 1969:exp 1	7:18-25
Holmberg & Wyon 1969:exp 2	7:18-25
Addition (error score)	
Wyon 1969*	6:18-24
Addition & memory (output)	
Trygg 1972:exp 3	38.0
Addition & memory (error score)	
Trygg 1972:exp 3	38.0
Addition & memory (RT)	
Trygg 1972:exp 2	38.0
Trygg 1972:exp 3	38.0
Reading speed	
Wyon 1969*	6:18-24
Reading comprehension	
Wyon 1969*	6:18-24
Concept attainment (correct answers)	
Wyon 1969*	6:18-24
Concept attainment (attempts)	
Wyon 1969*	6:18-24
Creativity (different answers)	
Wyon 1969*	6:18-24
Creativity (created information)	
Wyon 1969*	6:18-24
Programmed learning (rate of work)	
Pepler & Warner 1968	13:15-28
Programmed learning (error score)	
Pepler & Warner 1968	13:15-28
Paired-associates learning	
Wyon 1970	7:18-25
Decision taking (correct decisions)	
Griffiths & Boyce 1971:single task	9:14-23
Griffiths & Boyce 1971:peripheral task	9:14-23
Decision taking (error score)	
Griffiths & Boyce 1971	9:14-23

(continued next page)

Pepler 1958: slow, medium speed	9:24-33
Chiles 1958:exp 1	9:24-33
Bartlett & Gronow 1953	15:18-33
Chiles 1958:exp 2	19:24-43
Decision taking (omissions)	
Pepler 1958: medium,fast speed	9:24-33
Chiles 1958:exp 1	9:24-33
Chiles 1958:exp 2	19:24-43
Decision taking (time score)	
Bartlett & Gronow 1953	15:18-33
Letter coding (output)	
Viteles & Smith 1946	8:23-31
Letter coding (error score)	
Viteles & Smith 1946	8:23-31
Letter coding (variability score)	
Viteles & Smith 1946	8:23-31
Cognitive tracing (time score)	
Trygg 1972:exp 3	<u>38.0</u>
Cognitive tracing (error score)	
Trygg 1972:exp 3	<u>38.0</u>

Table 4. Studies of mental performance under heat stress yielding not statistically significant results. The right column presents the largest not significant effective temperature difference between the optimum temperature (stated first) and any other adverse temperature; underlined values refer to body temperature; asterisk (*) denotes experiments on interaction between heat and other stresses.

1. Holmberg & Wyon (1969)

(see above, Mental tasks: linear trend) did not find any significant difference in number of items attempted on a multiplication and an addition test at 18° and 25°C ET for either the younger or the older school children.

2. Wyon (1969)

(see above, Mental tasks: linear trend), investigating the effects of both heat (18° and 24°C ET) and noise (70 and 90 dB) on school children, reported no significant over-all effect of either of the two factors or any significant interaction effect between them on output or error score in an addition test.

3. Viteles & Smith (1946)

(see above, Mental tasks: linear trend) reported that both error and variability scores in a multiplication task were unaffected by approximately the same temperature difference as Wyon did, but on a higher heat stress level— 31°C compared with 23°C ET.

4. Chiles *et al.* (1972)

(see above, Mental tasks: significant results: no trend) did not find any significant over-all effect on multiplication speed or accuracy, even at such a large difference in ambient temperature as 17°C ET (between 19° and 36°C ET), although they reported a significant interaction effect for speed between air temperature, altitude, and subinterval, as mentioned above.

5. Trygg (1972)

(see above, Mental tasks: significant results: no trend), in a study of the effects of controlled hyperthermia on complex mental performance, found that a body temperature of about 38°C did not influence response latency in a combined addition and memory test. This result was verified by Trygg (1972) in a follow-up study using the controlled hyperthermia technique. However, Trygg in the follow-up study could not confirm his previously significant results with respect to number of items attempted and items correct (see Table 3); both output and error score were unaffected by a body temperature of 38°C , and no heat induced difference between personality groups was found.

Comments: Possibly the absence of statistically significant heat-induced effects on performance in the third study depended on a greater learning effect from trial to trial than was noted in the second study. This transfer effect might have masked a minor heat effect. Unfortunately Trygg did not

study this question.

Concerning the influence of heat on the performance of more and less able subjects, no significant differences were found, in contrast to the first controlled hyperthermia study.—In Trygg's studies, as well as in Wyon's, the subjects were free to work at their own pace, whereas time was probably a factor in the other studies.

Also, in some studies using verbal tasks, no statistically significant heat induced effects on mental performance have appeared (Table 4).

2. Wyon (1969)

reported that both speed and comprehension in a reading test were unaffected when the effective temperature was increased from 18° to 21° and further to 24°C . Nor did he find any statistically significant heat-induced change in concept attainment or creativity.

6. Wyon (1970)

reported no effect on paired-associates learning when studying two classes ($n = 30$) of 13-year-old school children exposed to air temperatures of 20° and 27°C DB in a language laboratory. Although Wyon did not give any data for air speed or humidity, the normal effective temperatures could be estimated at approximately 18° and 25°C , as the experiment was performed during the same period and in the same school as the Holmberg & Wyon (1969) study.

7. Pepler & Warner (1968)

(see above, Mental tasks: curvilinear trend), also investigating learning under heat load, did not report any change in rate of work or error score, even though the difference was as large as 13°C ET

between the coolest (15°C ET) and the warmest (28°C ET) of the six studied climates.

Comments: It is to be noted that, in all reviewed studies of verbal performance, the subjects performed the tasks at their own rate, and time was not stressed.

Finally, six studies of decision taking and coding are reviewed (Table 4).

8. Griffiths & Boyce (1971)

to test the hypothesis that performance under heat load is associated with comfort ratings on the environmental warmth, exposed fifty 20-40-year-old male subjects to five normal effective temperatures: 14° , 17° , 19° , 21° , and 23°C . As no information was given about the work rate on a psycho-motor task, no calculation of P4SR-values is possible, but it is noteworthy that the B4SR-values of all climates are well below zero. From a physiological standpoint, this means that the ambient heat stress imposed on the subjects was either very low or absent. In the latter case, it also implied that the subjects wearing normal indoor clothing, at least under some conditions, were losing heat instead of accumulating it. Each of the ten subjects in the five groups was singly exposed for about 90 minutes to only one condition according to the following procedure. First, they practised on a paced task measuring decision taking and attention; thereafter they practised on a psycho-motor tracking task. In the decision taking task, sets of three numbers were presented aurally, and the subject had to decide whether the numbers met one of two criteria. After a short period of rest, they carried out the two tasks simultaneously. Votes on comfort and thermal sensation were taken before and after the performance testing.

The results were:

a) Performance on the decision taking task was in no way influenced by the climate conditions. Both numbers of correct and faulty decisions were unchanged, irrespective of whether the task was performed singly or in combination with the tracking task.

b) Thermal sensation was linearly associated with environmental warmth ($r = .80^{xxx}$), whereas the correlation between comfort and ambient temperature was curvilinear ($r = .55^{xxx}$). Effective temperatures below 19°C —a condition perceived as thermally neutral—were rated "cool" or "too cool", whereas those above 19°C were rated "warm" or "too warm". No climate was, on average, rated "comfortable" on the comfort scale.

3. Viteles & Smith (1946)

presented a letter coding test to strongly motivated subjects who, for four hours, were exposed to 23° , 27° , and 31°C ET. No statistically significant effects were noted for any of the three performance measures (output, error ratio, and variation percentages), although body temperature and pulse rate were increased at both 27° and 31°C ET.

Comments: All performance measures were characterized by a substantial learning throughout the experimental period of three weeks, but according to Viteles & Smith, "the influence of such learning, so far as analysis of results is concerned, is made constant by the fact that the average position and deviation (in rank) of experimental trials are identical for each of the temperature conditions." This statement does not exclude the possibility of a great learning effect counteracting and masking a small heat effect.

9. Pepler (1958),
as previously indicated, did not find any heat-induced changes in a decision taking task with respect to:

a) error score at slow and medium speed of comparison,

b) number of missed comparisons at medium and high speed, although the temperature was raised 9° from 24° to 33°C ET .

10. Chiles (1958)

duplicated Pepler's (1958) study of high speed decision taking. However, he used only one speed of presentation of the test material, approximately corresponding to Pepler's medium speed. In his first experiment, 11 male students took part in four training sessions at normal room temperature before undergoing heat exposure at 24° , 27° , 30° , and 33°C ET , according to a repeated measure latin square design. The subjects, exposed to two different conditions a day, wore shorts during the one-hour long exposure; thus the P4SR-value of the four conditions would be about <0 , 0.4, 0.8, and 1.4 P4SR. After 30 minutes acclimatization, the performance test, lasting approximately 18 minutes, was administered during the second 30 minutes. In a second experiment, he exposed 10 male subjects to 24° , 27° , 34° , and 37°C ET , corresponding to <0 , 0.4, 2.1, and 3.0 P4SR, using the same procedure as before, except that the subjects were exposed to one temperature a day and had a further two training trials before the main experiments.

Number of omissions and error score were only slightly influenced by the heat—although the temperature difference between the coolest and the warmest climate was as large as 19°C ET — and no statistically significant differences were found in either of the

two experiments.

Comments: Chiles, to explain the discrepancy between his own and Pepler's study, referred to different choice of subjects, and to the fact that Pepler's enlisted naval men worked for somewhat longer periods at each trial. In addition to Chiles's explanation of his findings, the non-existent heat effects could possibly also be explained by the fact that, in the first experiment, a considerable and statistically significant learning effect appeared, which masked the temperature effect. Furthermore, the physical examination of the subjects who took part in Chiles's study was probably inadequate. When a third experiment of 43°C ET was performed, Chiles pointed out that "the two subjects who were unable to complete the runs stated that they had included a fair quantity of alcoholic beverages in their diets for the previous evening."

11. Bartlett & Gronow (1953)

studied the effects of heat stress on mental performance using an unpaced decision taking task. The subjects—16 RAF researchers—were given a matrix on which they had to imagine course and speed of airplanes moving vertically, horizontally, and diagonally, according to assigned rules.

They had to anticipate a) the number of collisions that would occur between the planes, b) which planes would be involved, and c) where the collisions would take place. In addition to error scores for a-c, the performance was given by d) decision time. According to a graeco-latin square design counteracting learning and fatigue effects, the subjects, in groups of four, were for one hour exposed to 23°, 28°, and 33°C ET; a room temperature ranging between 16° and 21°C DB was used as reference condition. The corresponding P4SR-values would be approximately <0, 0.5, 1.9, and

< 0, respectively, as the subjects wore shorts, socks, and shoes under thermal load and ordinary indoor clothing in the reference climate. The decision taking task was given during the final 30 minutes of heat exposure.

The analysis of variance performed showed no statistically significant main or interaction effects of heat on any of the four measures. According to Bartlett & Gronow, the non-existent temperature effect could be explained by the fact that their selective group of strongly motivated subjects and the absence of any learning effect indicated "that the majority of subjects were, in fact, comparable to Mackworth's "very good" or even "exceptionally skilled operator" (see below, Perceptual and non-motor tasks: linear trend, for a review of Mackworth's study). They also pointed out the unpaced character of the task and the relatively short exposure time.

Comments: Although Bartlett & Gronow discussed at length the significant effects of such load factors as number of planes and matrix size, they did not indicate the possibility that a performance-induced load effect concealed a heat-induced load effect.

5. Trygg (1972)

in the follow-up study (referred to as investigation 3) studied mental performance also by means of a cognitive tracing task. In a matrix of 225 squares, the female subjects had to connect 126 squares, according to instructions given in the squares. In some versions of the task, the instruction symbols and their meaning were concordant, i.e. U = up and R = right, whereas in other versions symbols and meaning were discordant, i.e. U = down and L = left.

Although the task was given during the first 20

minutes of the fourth exposure hour at controlled hyperthermia with a body temperature of 38°C , no statistically significant effect was found with respect to either time or error score. There was no statistically significant heat-induced difference between different personality classifications. Trygg suggested that the absence of any thermal effects depended on the fact that, after three hours of heat exposure, the subjects had reached a steady state with respect to body temperature.

Conclusions: The tasks that were not affected by the heat load imposed on the subjects in the studies reviewed above are of the same kind as those that were previously found to deteriorate under thermal stress.

Somewhat surprisingly, the average ambient temperature difference—about 10°C ET—between the most extreme climates not causing performance deterioration was twice as great as the average difference between conditions resulting in performance impairment. From the studies not causing performance deterioration presented in Table 4, it can be concluded that arithmetical and verbal work and tasks measuring decision taking and coding would not be affected even though the environmental temperature was, on average, increased from about 20 to 30°C ET.

It does not seem probable that the divergent findings could be explained by differences in acclimatization and exposure duration (or the time at which the tasks were allotted). Most studies have been performed with unacclimatized subjects; for studies in which acclimatized subjects participated, both statistically significant and not significant results were reported. In some studies lasting for as long as four hours (Viteles & Smith, 1946; Trygg, 1972), no statistically significant heat-induced changes were found for some

measures, whereas others were influenced.

What is the explanation of the difference between statistically significant findings presented in Tables 1 - 3 and not significant findings in Table 4?

a) Performance measures. Although the same kind of tasks have been used in studies reporting statistically significant and not significant results, the discrepant findings are in some cases due to different aspects of a performance task having been measured.

b) Motivational factors. Probably the absence of any heat effects partly depends on the subjects mostly being highly motivated and wishing to perform well, as some researchers have pointed out.

However, it is uncertain to what extent high motivation might counteract the adverse effects of heat stress on mental performance. Mackworth (1947) (see below, Perceptual and motor tasks: linear and curvilinear trends) has shown that even if high incentives improved performance under thermal load, the adverse effects of increased heat stress were not counteracted. This finding has proved true also for psycho-motor tasks. (Pepler 1958).

c) Pace of performance. Another fact which might explain the discordant findings is that many of the performance tasks which did not deteriorate were unpaced or self-paced.

It is well known that although the rate of work is the same for unpaced and paced tasks, subjects experience the two tasks differently and respond to them in dissimilar ways. On a self-paced task, the subject might, for instance, compensate for a short rest pause or a period of slow work rate by working faster. Thus the subject could maintain his average

standard rate of work on a self-paced task even if he is heat loaded, whereas a pattern of work similar to that suggested above would definitely result in a deteriorated performance on a paced task.

Psychologically, the pace load also adds to the thermal load and makes it more probable that the subject's performance will be affected.

d) Carry-over effects. The possibility of a great learning effect from trial to trial masking a small temperature effect has repeatedly been emphasized in the review. Almost every investigation has used an analysis of variance design, either permitting tests of temperature effects against a residual term free from learning or carry-over effects, or including an order or sequence factor which permitted learning to be studied separately.

Perceptual and non-motor tasks: linear trend

1. Viteles & Smith (1946)
2. Wyon (1969)
3. Mackworth (1946)
4. Wilkinson *et al.* (1964)
5. Colquhoun & Goldman (1972)
6. Bell *et al.* (1964)

Figures 3 and Table 5 present studies reporting statistically significant results implying a negative linear relation between ambient temperature and performance.

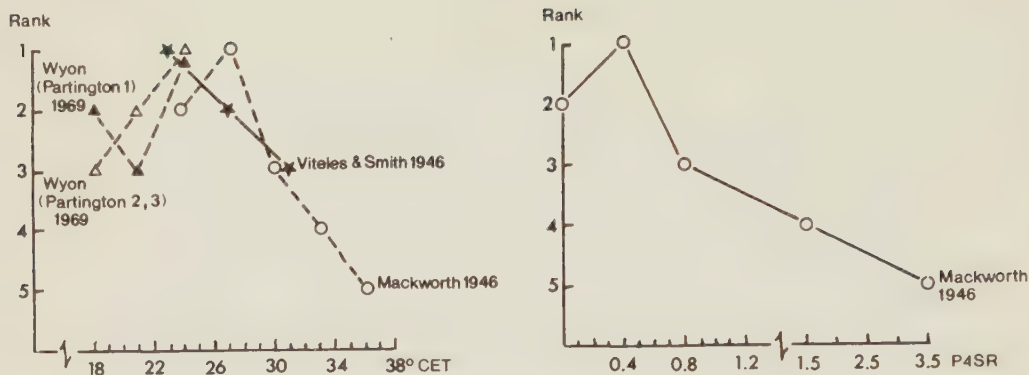


Figure 3. Linear trend between environmental heat—expressed in ET-units (3a) and P4SR-units (3b)—and perceptual and non-motor performance (rank 1 denotes optimum performance).

1. Viteles & Smith (1946),
(see above, Mental tasks: linear trend) studying cue-utilization by means of a number checking task, found that the performance output decreased slightly from 23° to 27°C ET; and at 31°C ET, the output was impaired by about 5% compared with the two cooler climates. They also found a reliable temperature effect on the variability of the number checking performance. The variability tended to increase with an increase in the imposed thermal stress.

2. Wyon (1969),
(see above, Mental tasks: linear trend) in contrast to Viteles & Smith, reported results implying a

positive relation between heat load and cue-utilization.

Using three versions of Partington's Pathways Test (see below, Psychological methods for measurement of performance, for a description of the test) he found statistically significant effects of the temperature factor, but not of the noise factor.

a) On the easiest and the most difficult versions, the performance was better at 24°C ET than it was at 18° or 21°C ET, whereas the difference in the performance on the two lower temperatures was not statistically significant. Therefore the trend is considered linear, although the performance was slightly worse at 21°C ET for the easiest version (Figure 3 a).

b) On the second, medium difficult version, no significant over-all effect of either temperature or noise was found, but again, a tentative linear trend appeared. Using basic probability reasoning, Wyon concluded "on the Null Hypothesis of no temperature effect and random assignments of groups to treatments, the probability of the observed result is 0.033 for a one-tailed test."

Comments: The different trends obtained by Viteles & Smith and Wyon are probably due to their having studied dissimilar temperature zones. It is to be noted that the significant optimum climate in both Viteles & Smith's and Wyon's studies was about 24°C ET. Because different slopes were found in the two studies, it seems reasonable to suggest that the relation between environmental temperature and perceptual performance was curvilinear instead of linear (Figure 3 a). This conclusion is tentatively supported by the following study.

3. Mackworth (1946)

studied the effects of heat on wireless telegraphy (W/T) operators taking morse messages. He tested 11 physically fit 18-24-year-old RAF volunteers. Although they were experienced, they were given further extensive W/T training (3 hours a day for 6 days a week for 5-7 weeks) at basic effective temperatures between 30° and 36°C , in order to artificially acclimatize them before the main experiments. These were performed at about 24° , 27° , 30° , 33° , and 36°C basic effective temperature (the subjects were dressed in shorts and gym shoes), but erroneously reported as higher normal effective values by Mackworth. The climates corresponding to 0, 0.4, 0.8, 1.5, and 3.5 P4SR, respectively, were presented in increasing order of severity. The exposure time at each exposure was three hours. During this time the subjects worked for 16 minutes with 3-minute rest periods in between.

The average number of mistakes was lowest at 27°C ET and increased with increasing heat load (Figure 3 a, b; Table 5). The error score was worse at 24°C ET, implying a curvilinear trend, but the difference between the two lowest temperatures was not statistically significant, and according to Mackworth, the error score bore a logarithmic, i.e. monotonically increasing, relation to environmental temperature:
 $\log \text{ performance} = 1.10768 + 0.09568^{\circ}\text{F (dry bulb)}.$

This trend and the fact that the average number of W/T errors per man per hour increased progressively from the first to the third hour of work were most pronounced for "competent" and "very good" operators, whereas the "exceptionally skilled" ones were hardly affected; day-to-day cumulative effects were absent.

As previously mentioned, no relation was found between rectal temperature and W/T performance. This was explained by Mackworth, who listed five reasons:

- a) Different people have entirely different levels of ability at W/T reception;
- b) heat-induced performance changes were partly determined by the subject's level of proficiency;
- c) progressively decreasing accuracy was related to operating ability;
- d) persistent individual differences in rectal temperature were found for different people;
- e) a rise in body temperature did not lead to performance deterioration until a rectal temperature of at least 38°C was obtained.

Comments: To this list could be added that the rectal temperature was not measured continuously as was performance, but only before and after each exposure. Furthermore, Mackworth based his results on absolute psychological and physiological readings, and used χ^2 -technique for statistical analyses. However, the last point probably does not explain the absence of a relation between body temperature and performance. The present author reached the same conclusion as Mackworth did when re-analysing the original data in terms of deviation measures and using correlation statistics.

4. Wilkinson *et al.* (1964)

(see above, Mental tasks: linear trend) reported positive and statistically significant Spearman rank order correlations between body temperature and performance at 21 minutes of auditory vigilance testing, implying a monotonic, but not necessarily linear, relation between these variables.

When the body temperature under controlled hyperthermia was raised above 37.3°C :

- a) The number of detected signals increased
($r = .50^*$)

b) The reaction time decreased ($r = .83^{***}$).

The improvement in both performance measures was significant at the highest body temperature level, 38.5°C , compared with the control level, and this difference was more marked at the fourth session than at the first one. Wilkinson *et al.* suggested that the unexpected improvement could be explained in terms of Duffy and Hebb's arousal hypotheses.

5. Colquhoun & Goldman (1972)

also studied vigilance under induced hyperthermia in an ambient environment of 39°C DB/ 34°C WB using 24°C DB/ 16°C WB as a "comfortably cool" control condition. As the air speed was 1.3 m/sec and the subjects—12 highly practised and heat acclimatized, 19-24-year-old, enlisted men—were dressed in shorts and slippers, these conditions approximately correspond to 35° and 16°C ET, respectively. Instead of using the Wilkinson *et al.* vapour-barrier technique for inducing hyperthermia, body temperature was raised by having the subject walk on a treadmill for either 0, 10, 20, or 30 minutes; thereafter they rested until the hour had elapsed. In the control condition, the effects of the physical work were checked by testing the subjects after 0 or 30 minutes treadmill work; otherwise the same experimental procedure was followed.

During the second hour of heat exposure, the subjects were continuously tested on the vigilance task according to the rating technique of signal detection theory. This experimental procedure was repeated daily for 14 days, except weekends, with the amount of physical work balanced in a latin square design.

The results indicated that:

a) Under heat load, the mean rectal temperature rose to 38°C when the first hour was spent at rest and increased further about 0.2°C for each 10

minutes of physical work, whereas

b) under the control condition, the total 30 minutes pre-test work resulted in a corresponding gain of 0.3°C .

During the second hour under heat load, the changes in heat store ranged from a mean net gain of 8 kcal without any physical work to a mean net loss of 9 kcal with 30 minutes work. The corresponding changes in the control condition were net losses averaging 10 and 20 kcal.

The vigilance test showed that all performance measures were rather similar under experimental and control conditions without any physical work. Although neither the detection rate nor the decrements that occurred within the sessions were associated with the induced hyperthermia, (Table 8) "certain" ratings were, and the trend was approximately linear (Table 5). The subjects reported significantly more "certain" answers and thus were more "confident" after 30 minutes of work with a body temperature of 38.6°C than in the resting heat condition with a body temperature of 38°C (cf. above, Wilkinson *et al.* 1964). However, also the false report rate increased monotonically with the amount of physical work and was statistically significant.

On the basis of these findings, Colquhoun & Goldman tested, by means of TSD-analysis, the hypothesis "that decisions to report a signal were being based on less adequate sensory evidence as the temperature of the body rose." The results completely confirmed the hypothesis:

a) The response criterion decreased monotonically and reliably with the length of the treadmill work, whereas

b) the sensory sensitivity (d') was unaffected by the induced hyperthermia.

Colquhoun & Goldman, referring to the study by Wilkinson *et al.* concluded, "that it is only when actual body-temperature increases that performance at a vigilance task will noticeably alter in hot environmental conditions, and, furthermore, that at least with highly trained subjects, the extent of this increase must be considerable before any such alteration occurs."

6. Bell *et al.* (1964)

reported two vigilance experiments; these are next reviewed.

In the first experiment, eight naval volunteers were tested for visual vigilance by means of a version of Broadbent's twenty dials test. For five consecutive days, the subjects, dressed in boiler suits, met the following ambient temperatures: 30°/25°, 43°/35°, 51°/37°, 51°/43°, and 63°/47°C DB/WB, in that order; the air speed was 0.25 m/sec, and the background noise amounted to about 90 dB. The heat stress cannot be expressed by means of ET or P4SR-values, as most conditions are beyond the range of these scales. After a weekend of rest, the programme was repeated for five more days.

Sitting alone, the subjects were exposed to each climate for as long as they could stand the heat load. Thereafter, they rested in a recovery room at 27°C until their oral temperature had fallen to a steady level, whereupon they were again exposed to the same condition. Provided the subject did not give up earlier, the exposure time was restricted to four hours. The exposure time for the five climates averaged 240, 188, 68, 28, and 19 minutes.

It was found that, although latency times tended to decrease with the heat load, neither this measure nor the mean percentage of missed signals was

reliably affected (Table 8). Bell *et al.* commented on the absence of any ambient temperature effects on performance by first referring to the fact that the subjects themselves stayed in the climate chamber as long as they could. Then they concluded: "it is likely, therefore, that they were in approximately the same average physiological condition during each climate exposure so that, assuming a physiological basis for behaviour, the same average vigilance performance in each climate would be expected."

The oral temperature recorded during the first 10 minutes differed between the five climates; therefore the performance measures during this short period were subjected to analysis of variance. None of the measures were attained statistically significant.

However, when trends were studied within the four hours of exposure, it was found at 30°/25°C—a condition approximately corresponding to 26°C ET and not causing any rise in oral temperature—that both measures of performance were influenced and increased monotonically from the first to the fourth hour of exposure.

a) For response time, reflecting both motor and perceptual processes, only the difference between the initial and the final hour was reliable.

b) For the average percentage of missed signals all paired comparisons with the first hour were statistically significant.

Because corresponding analyses were lacking for the other conditions, it cannot be concluded that these effects were temperature-induced. They could equally well be time-induced fatigue effects, as Bell *et al.* also recognized.

Definitely reliable and clearcut results were obtained when the two measures of performance, instead of being

related to the ambient temperature, were analysed with respect to four oral temperature intervals: $< 37^{\circ}$, 37° - 37.49° , 37.5° - 37.99° , and $\geq 38^{\circ}\text{C}$.

In contrast to the results presented by Colquhoun & Goldman, and Wilkinson *et al.* in particular, the percentage of omissions and the median response time both increased—positively accelerated—with an increase in oral temperature. Paired comparisons were statistically significant for:

a) Percentage of missed signals between $< 37^{\circ}$ and the two highest oral temperature intervals, and between 37° - 37.49° and $\geq 38^{\circ}\text{C}$

b) Response time between the 37° - 37.49° interval and the two higher oral temperature intervals (Table 5).

In the second experiment by Bell *et al.* a further eight volunteer naval men were studied with respect to auditory vigilance. Dressed in boiler suits, they attended daily at one of the environmental temperatures: $37^{\circ}/30^{\circ}$, $43^{\circ}/35^{\circ}$, $50^{\circ}/37^{\circ}$, $53^{\circ}/40^{\circ}$, and $56^{\circ}/43^{\circ}\text{C}$ DB/WB, in increasing order of heat load; the air speed was 0.75 m/sec and the background noise amounted to approximately 90 dB. The programme was repeated for a fortnight, except for weekends.

Compared with the first experiment, the procedure was somewhat modified, so far that at first the subjects were exposed, continuously standing, at a metabolic cost of 126 kcal/h until they gave up. On average, this occurred after 240, 151, 53, 27, and 19 minutes of exposure in the five climates. After resting in the recovery room at 27°C until the oral temperature had dropped to a steady level, they were exposed a second time, but this time were required to step on and off a stool at a metabolic cost of 282 kcal/h. The tolerance times were now 240, 55, 31, 20, and 15 minutes, respectively. At both sessions, the subjects attended the climate chamber in pairs.

Because about 50% of the presented acoustic signals were missed, the vigilance performance was expressed only by means of the proportion of missed signals. Furthermore, all data obtained with regard to physical work at the lower metabolic rate in the mildest climate were discarded, as only two subjects participated under these conditions.

Although statistical significance was attained in the performed analyses of variance, both for standing and stepping conditions, the relation between ambient temperature and vigilance performance was ambiguous, as no consistent trend appeared. Paired comparisons of the temperatures revealed that the optimum climate for signal detection was $56^{\circ}/43^{\circ}$ DB/WB:

a) Under standing conditions, this climate differed from both $50^{\circ}/37^{\circ}$ and $56^{\circ}/43^{\circ}$ C, i.e. the trend was so far quadratic.

b) Under stepping sessions, the mean percentage of signals was reliably worse at the hottest climate — $56^{\circ}/43^{\circ}$ C—compared with $43^{\circ}/35^{\circ}$ and $53^{\circ}/40^{\circ}$ C.

Analyses of the vigilance data with regard to oral temperature instead of ambient temperature again revealed a definite linear relation between degree of physiological strain and perceptual but non-motor performance. The average proportion of missed signals in the four oral temperature intervals were:
 $< 37^{\circ}$ C: 30.5%; 37° – 37.49° C: 40.5%; 37.5° – 37.99° C: 42.7%; $\geq 38^{\circ}$ C: 43.2%.

The performance at the highest temperature, $\geq 38^{\circ}$ C, was worse than at the two lowest oral temperature intervals. Moreover, the difference between $< 37^{\circ}$ and the interval 37.5° – 37.99° C was statistically significant too (Table 5).

Referring to the contradictory findings in the Wilkinson et al. study, Bell et al. briefly concluded their report: "the particular results in any given situation may well depend --- on the type of test and the conditions of testing used."

Comments: The discordant findings of Bell *et al.* compared with Colquhoun & Goldman and Wilkinson *et al.* might, in addition to differences in design and procedure, be due to the background noise in the experiments by Bell *et al.* being very high; being, in fact, in the risk zone of hearing damage at prolonged exposure.

Perceptual and non-motor tasks	^o C ET
Number checking (output)	
Viteles & Smith 1946	4:27-31
Number checking (variability score)	
Viteles & Smith 1946	8:23-31
Morse code reception (error score)	
Mackworth 1946	6:24-30
Vigilance (false reports)	
Colquhoun & Goldman 1972	0.6:38.0-38.6
Vigilance (omissions)	0.5-1.0:
Bell <i>et al.</i> 1964	37.0-(37.5-37.99)
Vigilance (RT)	0.0-1.0:
Bell <i>et al.</i> 1964	(37.0-37.49) - - (37.5-37.99)
Vigilance ("certain" answers)	
Colquhoun & Goldman 1972	0.6:38.0-38.6
Auditory vigilance (detections)	
Wilkinson <i>et al.</i> 1964	2:38.5-36.5
Auditory vigilance (omissions)	3:50/37-53/40
Bell <i>et al.</i> 1964: standing	3:53/40-56/43
Bell <i>et al.</i> 1964: working	3:53/40-56/43
Bell <i>et al.</i> 1964	0.5:37.0-(37.0-37.49)
	(37.5-37.99)-38.0
Auditory vigilance (RT)	
Wilkinson <i>et al.</i> 1964	2:38.5-36.5
Pathways test 1, 2, 3 (output)	
Wyon 1969*	3:24-21

Table 5. Studies of perceptual-and-non-motor performance under heat stress yielding statistically significant results ($p < 0.05$) interpreted to indicate a linear relation between heat stress and perceptual-and-non-motor performance. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature; climates outside the range of the ET-scale are stated in DB/WB temperatures; underlined values refer to body temperature; asterix (*) denotes experiments on interaction between heat and other stresses.

Conclusions: Although the trend was considered linear in the first three studies reviewed above, the graphical representation of the results in Figure 5 suggests a curvilinear relation between ambient temperature and perceptual performance. The optimum effective temperature zone lies between 24° and 27°C .

A change in the effective temperature by about 3°C in either direction would probably impair the performance (cf. Mental tasks:linear trend).

Moreover, the last three reviewed studies clearly reveal that the relation between body temperature and perceptual performance must be considered causal, even if the findings of Mackworth contradict that conclusion. The more sophisticated experimental techniques of induced and controlled hyperthermia, including continuous recording of the physiological strain, used in the last three studies must be considered both more valid and more reliable than the experimental and statistical techniques adopted by Mackworth.

Because of the discordant findings between Wilkinson *et al.* and Colquhoun & Goldman, on one hand, and Bell *et al.*, on the other, the nature of the relation between physiological strain and performance remains to be clarified, i.e. whether it is linear or curvilinear, and whether it is positive or negative. However, it must be considered indisputable, even if Mackworth's result are taken into account, that body temperatures exceeding 38.5°C , and probably even 38°C , definitely affect the perceptual and cognitive processes of man.

Concerning the nature of the relation, it seems most probable with the TSD-analysis in the Colquhoun & Goldman study considered and on the basis of the consistently negative relations found in the studies by Mackworth and Bell *et al.*—that the relation is linear and negative, i.e. that perceptual performance is impaired the more the body temperature is elevated above at least 38°C . However, several factors, such as type of test, conditions of testing, and individual characteristics of the subject, might modify the results obtained in heat stress research. In fact, it cannot be excluded that the relation between body

temperature and perceptual performance is curvilinear, as was previously suggested to be the case for the relation between ambient temperature and perceptual performance. Unfortunately, the data in the reviewed studies are too scanty to permit analysis of this question.

Perceptual and non-motor tasks: curvilinear trend

1. Mackworth (1950)
2. Pepler (1958)
3. Viteles & Smith (1946)

Statistically significant curvilinear trends have appeared in three studies as shown in Figure 4 a, b and in Table 6.

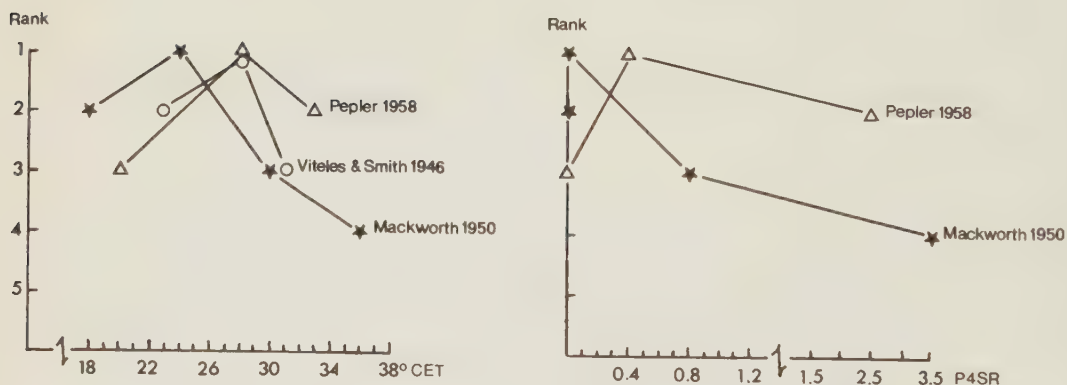


Figure 4. Curvilinear trend between environmental heat—expressed in ET-units (4a) and P4SR-units (4b)—and perceptual and non-motor performance (rank 1 denotes optimum performance).

1. Mackworth (1950)

performed the first study to be reviewed. A total of 89 naval ratings aged 18-29 years, wearing shorts under heat load, were put into four approximately equal groups, each exposed to one of the studied atmospheric conditions: 18° , 24° , 30° , and 36°C ET , corresponding to approximately <0 , 0 , 0.8 , and 3.5 P4SR, respectively. (Even in this study, Mackworth erroneously reported normal instead of basic effective temperatures.) During the two hours of thermal exposure, loss of alertness was tested by means of a visual vigilance task: the Clock Test. Before the main experiment, the subjects practiced for two hours at normal room temperature; they were also artificially heat acclimatized at 27° - 36°C ET for two hours a day for a fortnight.

The effective temperature of 24°C proved to be the optimum condition for performance. Statistical significance testing confirmed that the mean percentage of missed signals was definitely fewer at 24°C ET than at higher and also at lower temperatures (Figure 4 a, b; Table 6).

In all climates, the number of missed signals increased from the first to the second hour of exposure, but this increase was statistically significant only at 30° and 36°C ET .

It also appeared that, during the final 30 minutes at these two conditions, inexperienced non-look-outs missed more signals than experienced look-outs. So far, this result confirmed the previously referred to conclusion in the W/T reception study (see above, Perceptual and non-motor tasks: linear trend), implying that more competent subjects more easily endure the adverse effects of heat exposure on perceptual performance than do less competent subjects.

Comments: The high incidence of missed signals at 18°C ET was suggested by Mackworth to depend on uncomfortable feelings of cold, as the average fall in body temperature was about 0.5°C. It is rather remarkable that Mackworth attributed performance decrements in cold climates to changes in body temperature, but for hot climates, emphasised that the relation was non-causal.

2. Pepler (1958),
in a study on eight naturally acclimatized men at Singapore, confirmed the results on the Clock Test presented by Mackworth on artificially acclimatized men. The subjects, dressed in shorts and sandals, were tested for two hours on the visual watch-keeping task at each of three effective temperatures: 19°, 28°, and 33°C, corresponding to <0, 0.4, and 2.6 P4SR, respectively.

The middle climate was found to be the optimum condition (28°C ET). Here, there was a fewer number of missed signals than in both the cooler and the warmer climates, which did not differ (Figure 4 a, b; Table 6). Pepler's results also confirmed the previous findings by Mackworth in England that the mean number of signals per 30-minute period increased progressively from the first to the last hour, but the increase was lowest in the optimum climate.

As both the final rectal temperature and the total sweat loss increased monotonically with the heat stress, whereas prolonged visual watch-keeping and heat stress showed a quadratic relation, Pepler concluded: "there was no direct association between the changes in performance and these simple physiological measures."

Comments: The facts reported by Pepler do not exclude the possibility of a relation between simultaneous readings of performance and heat strain measures; this

relation was not studied by Pepler. The total sweat loss and, in particular, the final rectal temperature reflect the physiological condition of Pepler's subjects at the termination of the exposure. These parameters give poor information about how heat strain influenced perceptual performance during the exposure. This criticism is not restricted to Pepler's study, but is valid for most investigations in the field of heat stress research (see also below, Statistical techniques for analysis of the relation between physiological strain and performance).

3. Viteles & Smith (1946)

(see above, Mental tasks:linear trend) reported results on a perceptual pursuit test or maze tracing task indicating a curvilinear trend. The optimum climate with respect to output proved to be the middle climate with an effective temperature of 27°C. The performance in this condition was better than at 31°C ET, whereas the difference from the lower temperature —23°C ET—approached significance (Figure 4 a; Table 6). The two extreme climates did not differ.

Perceptual and non-motor tasks	°C ET
Vigilance (omissions)	6:24-18
Mackworth 1950	24-30
Pepler 1958	5:28-33
Maze tracing (output)	
Viteles & Smith 1946	4:27-31

Table 6. Studies of perceptual-and-non-motor performance under heat stress yielding statistically significant results ($p < 0.05$) interpreted to indicate a curvilinear relation between heat stress and perceptual-and-non-motor performance. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature.

Conclusions: In summary, the three investigations showing curvilinear trends indicate that, for predominantly perceptual and non-motor tasks, the optimum atmospheric condition averages 26°C ET and ranges from 24° to 28°C ET. A change of about 5°C in the heat load from 26°C ET in either direction will probably give rise to a significant adverse effect on performance. This conclusion agrees well with the conclusion drawn on the basis of the studies reviewed in the preceding section.

The increase in number of missed signals from the first to the second hour of exposure, reported by Mackworth and Pepler to appear in all climates, but being statistically significant only at 30°C ET or higher ambient temperatures, indicates that heat stress could strengthen fatigue effects. However, it cannot be concluded that the performance deterioration was due to thermal fatigue. It could also be due to a heat-induced reorganization of the physiological and psychological function in particular, as the heat effect *per se* appeared during the first hour.

Perceptual and non-motor tasks: significant results:
no trend

1. Holmberg & Wyon (1969)
2. Bursill (1958)
3. Trygg (1972)
4. Poulton *et al.* (1974)

The review of significant results with respect to perceptual and non-motor tasks will now be ended by the presentation in Table 7 of studies so designed that it is impossible to analyse the heat stress-performance relation.

Perceptual and non-motor tasks	^o C ET
Number checking (output)	
Holmberg & Wyon 1969:exp 2	7:18-25
Peripheral lights (omissions)	
Bursill 1958:exp 1	17:18-35
Bursill 1958:exp 2	17:18-35
Peripheral lights (RT)	
Trygg 1972:exp 2	<u>38.0</u>
Auditory vigilance (detections)	
Poulton <u>et al.</u> 1974 [*]	15:18-33
Auditory vigilance (false detections)	
Poulton <u>et al.</u> 1974 [*]	15:18-33

Table 7. Studies of perceptual-and-non-motor performance under heat stress yielding statistically significant results ($p < 0.05$) without indicating any trend in the findings. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature; underlined values refer to body temperature; asterisk (*) denotes experiments on interaction between heat and other stresses.

1. Holmberg & Wyon (1969)

found in the experimental field study on school children that the perceptual speed on a number checking task decreased when the ambient temperature increased from 18^oC ET (< 0 P4SR) to 25^oC ET (0.4 P4SR). The temperature effect interacted with the time effect implying that the children were far more adversely influenced by the heat in the afternoon than in the morning.

2. Bursill (1958)

was one of the first in the field of heat stress research to use a peripheral task to which the subjects had to respond concurrently with a continuous central task. The peripheral task consisted of six small lamps randomly lit and placed in a semi-circle at eccentric angles of 20^o, 50^o, and 80^o left and

right in front of the subject. A conventional pursuitmeter was used as the central task. Bursill exposed eighteen 18-32-year-old naval volunteers. They were artificially heat acclimatized for three hours a day over a period of 14 days before the main experiments. For five consecutive days in both the first and the third experiments, six subjects were exposed to 35°C ET stripped to the waist, and to 18°C ET lightly clad. It is difficult to express the experimental conditions by means of the P4SR-scale, because the metabolic rate due to the performance testing and in particular the pursuitmeter task was not stated.

The results of the first experimental session at 35°C ET were used for practice and examination purposes; therefore the remaining four sessions were balanced in an ABBA-design. After a one-hour rest in darkness (for dark adaptation) the subjects twice faced ten 4-minute samples of performance testing; the total exposure time under heat load thus amounted to approximately 150 minutes. The first and third experiment differed, because the pursuitmeter speed was fast in the first experiment and slow in the third. The second experiment was similar to the first, except that the subjects spent two hours of heat exposure at rest, and a sixth day of performance testing at 35°C ET was added. Furthermore, the intensity of the peripheral lamps was slightly increased.

A statistically significant heat induced increase in the total number of missed peripheral signals was noted in the first and second experiment (Table 7), whereas the percentage of confused signals was not affected (Table 8).

In both experiments, particularly in the second one, the adverse temperature effect was progressive, being approximately twice as large during the second 4-minute time sample compared with the first. However, the

temperature effect appeared already during the second 4-minute period in the first sample. Bursill therefore suggested that thermal load gives rise to a functional reorganization of the behaviour in combination with a progressively increasing thermal fatigue.

Moreover, it was found that the percentage of missed peripheral signals increased the further away the lamp was from the point of fixation, a phenomenon termed "funnelling of attention" by Bursill. This funnelling was more marked under heat load and increased progressively with the length of exposure, being most distinctive after two hours of exposure at 35°C ET. According to Bursill, the heat induced restriction in the field of perception "must be due to alterations in central levels of attention, and not to local alterations in the eye."

Bursill pointed out that the subjects showed consistent response patterns on the peripheral and the central task, but the two tasks were not directly associated. The results on the central pursuit task are presented below (see the section headed Perceptual and motor tasks: significant results: no trend).

3. Trygg (1972)

(see above, Mental tasks: significant results: no trend) used the Bursill technique of simultaneous presentation of a central and a peripheral task in the above-mentioned follow-up study of the effects of controlled hyperthermia. The central task consisted of an auditory vigilance test presented in two 10-minute periods, whereas the Bursill lamp test formed the peripheral task during the second of the two 10-minute periods. In addition to shorter periods of testing, Trygg's study differed from Bursill's in two other respects: instead of six lamps, Trygg used ten; he also introduced frequency bias in the

signals by presenting the four central lamps more often than the six peripheral lamps. The two tasks were administered after 60, 120, and 210 minutes of controlled hyperthermia at a body temperature of 38°C.

Trygg reported a statistically significant heat-induced increase in reaction time during the second hour of exposure (Table 7); subjects with signs of a hysteroid personality were most affected. However, in contrast to Bursill, he did not find that the temperature effect increased with the length of exposure. Nor did Trygg find any difference in reaction time between the four central and the six peripheral lights, i.e. the funnelling of attention was not influenced by the heat load. This, Trygg explained, depended on:

- a) The short periods of testing,
- b) the frequency bias in favor of the central lamps, and
- c) the increased number of lamps making the task so difficult and fogging that the heat load did not add much to the total stress.

Comments: In addition to these reasons explaining differences in results, it should be emphasised that Bursill recorded the number of missed signals for his male subjects, a measure being more centred around perceptual processes than the reaction time measured by Trygg, which incorporated also the motoric functioning of the female subjects. In fact no signals were missed in Trygg's study, as a light was on and the reaction time measured until the subject reacted and pushed the response button.

4. Poulton *et al.* (1974),
studying the interaction of the loss of a night's sleep with mild heat, exposed twelve 18-35-year-old enlisted

naval men to a basic effective temperature of 33°C , corresponding approximately to 1.5 P4SR. In the control condition, the men were exposed, fully clad, to a normal effective temperature of 18°C or less than 0 P4SR. The ear temperature was recorded but unfortunately was not presented, commented on, or related to performance changes.

Statistically significant main effects of temperature were noted with respect to detection rate on the Wilkinson auditory vigilance task. This task, lasting 30 minutes, was administered after a full hour of performance testing including, in addition to watch-keeping, also tracking with peripheral lights and a serial reaction task (reviewed below under the heading Perceptual and motor tasks: significant results: no trend).

The average percentage of detected signals decreased under heat load. Furthermore, during the first 15 minutes of testing, a reliable interaction was found between sleep deprivation and thermal stress. When the two stressors occurred together, the adverse effect on the detection rate was less than the detrimental effects produced by each of the stressors. However, the interaction pattern changed from the initial to the final 15 minutes, implying that combining sleep deprivation and heat stress gave a greater but not additive adverse effect than either stress by itself.

Because false detections increased in heat during the first and last 15 minutes of testing and because this temperature effect decreased from beginning to end, Poulton *et al.* plotted ROC-curves. The curves indicated that the sensory sensitivity (d') at the beginning was greater for loss of sleep and temperature combined than for either of them separately, whereas at the end, the reverse relation was valid. On account of these results, Poulton *et al.*, emphasised that,

concerning the much debated question whether heat is arousing or dearousing: "the reliable interaction between the heat and the loss of sleep at the start of the vigilance task, indicates that the heat is a behavioural arouser." However, they also stated: "it would be an oversimplification to attempt to explain all stress effects in terms of the single dimension of behavioural arousal."

Conclusions: According to the reviewed studies, perceptual and non-motor tasks are more efficiently achieved in a cooler ambient environment of 18°C ET than under heat load at room temperatures around 30°C ET. On account of the great temperature differences between the climates studied, ranging from 7° to 17°C ET, no conclusion can be drawn concerning an optimum ambient temperature. Furthermore, Trygg's results tentatively indicate that not only environmental parameters, but also individual characteristics such as personality, determine the subject's reaction.

Concerning the relation between exposure duration and performance, three different results have been reported:

a) Progressively increasing effects of heat stress on the number of missed peripheral lights (Bursill 1958);

b) No relation between exposure duration under controlled hyperthermia and reaction time to peripheral lights (Trygg 1972);

c) Progressively decreasing effects of heat stress on false detections in an auditory vigilance task (Poulton *et al.* 1974).

The divergent findings are perhaps due to the use of different procedures and performance measures and call for a standardization of the experimental technique in heat stress research.

Perceptual and non-motor tasks: not statistically
significant results

1. Holmberg & Wyon (1969)
2. Viteles & Smith (1946)
3. Bursill (1958)
4. Azer *et al.* (1972)
5. Poulton *et al.* (1974)
6. Colquhoun & Goldman (1972)
7. Bell *et al.* (1964)
8. Loeb & Jeantheau (1958)
9. Trygg (1972)

In several investigations reporting reliable temperature effects for some perceptual performance measures, the influence of other measures have been found to be statistically not significant, as is evident from Table 8.

Perceptual and non-motor tasks	°C ET
Number checking (output)	
Holmberg & Wyon 1969:exp 1:task 1	7:18-25
Holmberg & Wyon 1969:exp 1:task 2	7:18-25
Number checking (error score)	
Viteles & Smith 1946	8:23-31
Dot localization (output)	
Viteles & Smith 1946	8:23-31
Dot localization (error score)	
Viteles & Smith 1946	8:23-31
Dot localization (variability score)	
Viteles & Smith 1946	8:23-31
Peripheral lights (omissions)	
Azer <u>et al.</u> 1972	11:21-32
Bursill 1958:exp 3	17:18-35
Peripheral lights (error score)	
Bursill 1958	17:18-35
Peripheral lights (RT)	
Poulton <u>et al.</u> 1974*	15:18-33
Azer <u>et al.</u> 1972	11:21-32
Vigilance (detections)	
Colquhoun & Goldman 1972	<u>1.0:37.6-38.6</u>
Vigilance(omissions)	
Bell <u>et al.</u> 1964	33:30/25-63/47
Vigilance (RT)	
Loeb & Jeantheau 1958	15:16-31
Bell <u>et al.</u> 1964	33:30/25-63/47
Colquhoun & Goldman 1972	<u>1.0:37.6-38.6</u>
Vigilance (sensory sensitivity-d')	
Colquhoun & Goldman 1972	<u>1.0:37.6-38.6</u>
Auditory vigilance (detections)	
Trygg 1972:exp 2	<u>38.0</u>
Auditory vigilance (omissions)	
Trygg 1972:exp 2	<u>38.0</u>
Maze tracing (error score)	
Viteles & Smith 1946	8:23-31
Maze tracing (variability score)	
Viteles & Smith 1946	8:23-31
Binocular visual acuity	
Colquhoun & Goldman 1972	<u>1.0:37.6-38.6</u>
Defence mechanisms (stress score)	
Trygg 1972	<u>38.0</u>

Table 8. Studies of perceptual and non-motor performance under heat stress yielding not statistically significant results. The right column presents the largest not significant effective temperature difference between the optimum temperature (stated first) and any other adverse temperature; climates outside the range of the ET-scale are stated in DB/WB temperatures; underlined values refer to body temperature; asterix (*) denotes experiments on interaction between heat and other stresses.

1. Holmberg & Wyon (1969)

(see above, Mental tasks: linear trend) reported no significant change of the output on two different number checking tasks for 8-9-year-old children, when the classroom temperature was elevated 7°C—from 18°C to 25°C ET, corresponding to <0 and 0.4 P4SR, respectively—but the same rise impaired the same performance for 11-12-year-old children (Table 7).

2. Viteles & Smith (1946)

(see above, Mental tasks: linear trend) found that the error score on a number checking task was not affected, when the ambient temperature was increased from 23°C to 27°C and further to 31°C ET, but both the output and the variability measures were (Table 5). Viteles & Smith did not find any statistically significant change of either error score or variability score on a perceptual pursuit or maze tracing task for which a reliable quadratic trend appeared with respect to the output measure (Table 6). For a third perceptual and non-motor task—dot localization—no statistically significant temperature effect was noted for any of the three performance measures.

3. Bursill (1958)

(see above, Perceptual and non-motor tasks: significant results: no trend) reported no temperature-induced "funnelling of attention" or any other performance changes in the third experiment, performed on peripheral vision during exposure to hot and humid conditions, which was the case in the first two experiments (Table 7).

Comments: The absence of any environmental effects, despite a room temperature increase of 17°C—from 18°C to 35°C ET—might be because, in the third experiment, the pursuitmeter speed on the central task was slow, whereas in the first two experiments, it was fast. Therefore, the perceptual load was decreased and the

subjects could focus their attention more on the peripheral task, which became easier and the peripheral vision was not so easily disturbed by the heat load.

4. Azer *et al.* (1972)

duplicated the Bursill experiments with a central tracking task concurrently executed with peripheral watch-keeping. In all, twentyone 18-25-year-old male students, wearing the same uniform (0.6 clo) were put into three groups of seven. Each group was exposed once to one of three experimental climates: 29°, 31°, and 32°C ET, and also to a control climate of approximately 21°C ET. After attachment of the physiological gauges for recording rectal and skin temperatures, pulse rate, and sweating each subject waited for 15 minutes in a pre-test room of about 24°C DB before entering the climate chamber. He then practiced for 25 minutes on the two tasks, whereon his performance was tested for 100 minutes. The subjects worked in 20-minute cycles: 15 minutes of tracking and simultaneous watch-keeping were followed by a 5-minute rest.

In all conditions the thermal sensation and the physiological measures were increased compared with the control conditions, except for the rectal temperature, which was not reliably elevated at 29° and 31°C ET.

Concerning the peripheral watch-keeping however, no statistically significant heat-induced effects were noted with respect to either funnelling of attention or the mean percentage of omissions or reaction time, except that the average latency time of the last cycle at 31°C ET—the condition at which the rise in rectal temperature was significant— was longer than the average score of all five cycles in the control conditions (Table 8).

Comments: However, because no over-all F-test was performed, but all 18 pairwise comparisons in the data snooping were based on simple t-tests, this result is considered highly spurious. Testing at the 0.05 probability level, as Azer *et al.* did, results on average in one significant comparison by change out of 20 performed.

Despite the lack of analyses of correlation and regression, Azer *et al.* concluded "there was no correlation between the physiological responses and deterioration in performance." Then they somewhat cryptically ended their report: "However, only the heat stress of the 95°F to 75% RH¹⁾ had a significant effect on performance. This was also the only heat stress environment that caused a significant increase in rectal temperature."

The discordant findings of this study compared to Bursill's first two experiments might be explicable in terms of differences in procedure and apparatus and can also be because Azer *et al.* studied lower degrees of thermal load.

5. Poulton *et al.* (1974)

(see above, Perceptual and non-motor tasks: significant results: no trend) found, in a study of interaction of sleep deprivation and heat, that no temperature effect at 33°C ET appeared with regard to response time—**missed signals were not recorded**—on Bursill's peripheral lights, again used as a secondary task together with tracking.

6. Colquhoun & Goldman (1972)

7. Bell *et al.* (1964)

In the study by Colquhoun & Goldman (1972) on vigilance

1) 95°F, 75% RH = 32°C ET

under induced hyperthermia and in the study by Bell *et al.* (1964) on the relation between heat tolerance limits and vigilance—both discussed at length above under the heading Perceptual and non-motor tasks: linear trend—no reliable thermal effects were found on response time. Despite a significant change in confidence in the first study (Table 5), the detection rate and the sensory sensitivity were unaffected, as was the mean percentage of visual signals missed in the second study, whereas the mean percentage of missed auditory signals was affected.

Concerning the Colquhoun & Goldman study, it can be added that a binocular visual acuity test, performed after the vigilance test, was unaffected by the induced hyperthermia. The authors emphasized this negative finding and pointed out that though peripheral sensory functions do not change under hyperthermia, central cognitive processes, i.e. decision taking and response criteria, could be influenced.

8. Loeb & Jeantheau (1958)
reported no thermal effects on vigilance in an experimental field study. These researchers studied the influence of different combinations of noise, vibration, heat, and time of day on signal detection. With respect to temperature and humidity, the control condition was fixed at 18°-24°C DB, 4%-24% RH, and noise at 65-75 dB, whereas the experimental noise was 115-125 dB, and the experimental heat ranged from 43° to 51°C DB, 4%-24% RH. Because either air speed or clothing of the 12 army subjects participating under all conditions were given, ET or P4SR-values cannot be exactly calculated, but a rough estimate of the normal effective temperatures would be approximately 16° and 31°C.

No significant change of the median response time on Broadbent's twenty dials test was noted under heat

load (exposure duration 225 minutes).

9. Trygg (1972)

(see above, Mental tasks: significant results: no trend) reported no statistically significant differences in number of detected or missed auditory signal on a vigilance test comparing an experimental hyperthermia group with a control group. Nor did he find any reliable change in the operation of psychical defense mechanisms when the body temperature was raised from a normal level to 38°C.

Conclusions: In summary, it can again be stated, as it previously was for mental tasks, that, where adverse effects of heat load on the tasks were not significant, these tasks might represent the same sort of tasks as were found to deteriorate. So far, it can be inferred that mental, perceptual and non-motor, and psycho-motor tasks are to be treated separately. If so, the type of task within these groups is not crucial concerning whether or not performance will change under thermal load. Instead, it has repeatedly been established that different measures of one and the same task can be influenced not only in different degrees, but also in different directions, i.e. different measures might be of dissimilar sensitivity and, moreover record different aspects of performance. The most relevant aspects of a performance task thus seem to be its dynamic characteristics—reflected by performance measures—and not its structural characteristics. Therefore, it must be considered a basic fact that the results obtained in different investigations are comparable only on the supposition that the same type of measure of the same type of task has been used with otherwise identical procedures and subjects. However, this does not mean that analyses and syntheses are excluded in heat stress research, but only that many different environmental, task, and individual variables must be taken into

consideration, more than is usually the case. Some standardization in design, procedure, and choice of apparatus and subjects is necessary.

A comparison of reliable and unreliable findings (see Tables 4 and 8, respectively) reveals that, as was also the case for mental tasks, the mean difference in ambient temperature between the most extreme climates not causing performance changes—about 13°C ET—was almost twice as great as the average difference between conditions resulting in altered achievement.

However, it should be noted that, provided the heat stress-perceptual performance relation is curvilinear, as was previously suggested, this is what can be expected. A number of not statistically significant findings have occurred in investigations in which high and low but not medium—optimum—temperatures were investigated. Probably, this is only one part of the explanation behind the discordant results and other reasons should be sought among the previously referred to factors.

Perceptual and motor tasks: linear and curvilinear trends

1. Viteles & Smith (1946)
2. Griffiths & Boyce (1971)
3. Mackworth (1950)
4. Carpenter (1950)
5. Pepler (1958)
6. Mackworth (1947)

The results of most studies of the effects of heat on perceptual and motor performance show that a linear trend is formed if more than two climates are involved. Therefore, the review of statistically significant

results presents linear and curvilinear findings in the same section. Figure 5 illustrates the trends; Table 9 summarizes the results.

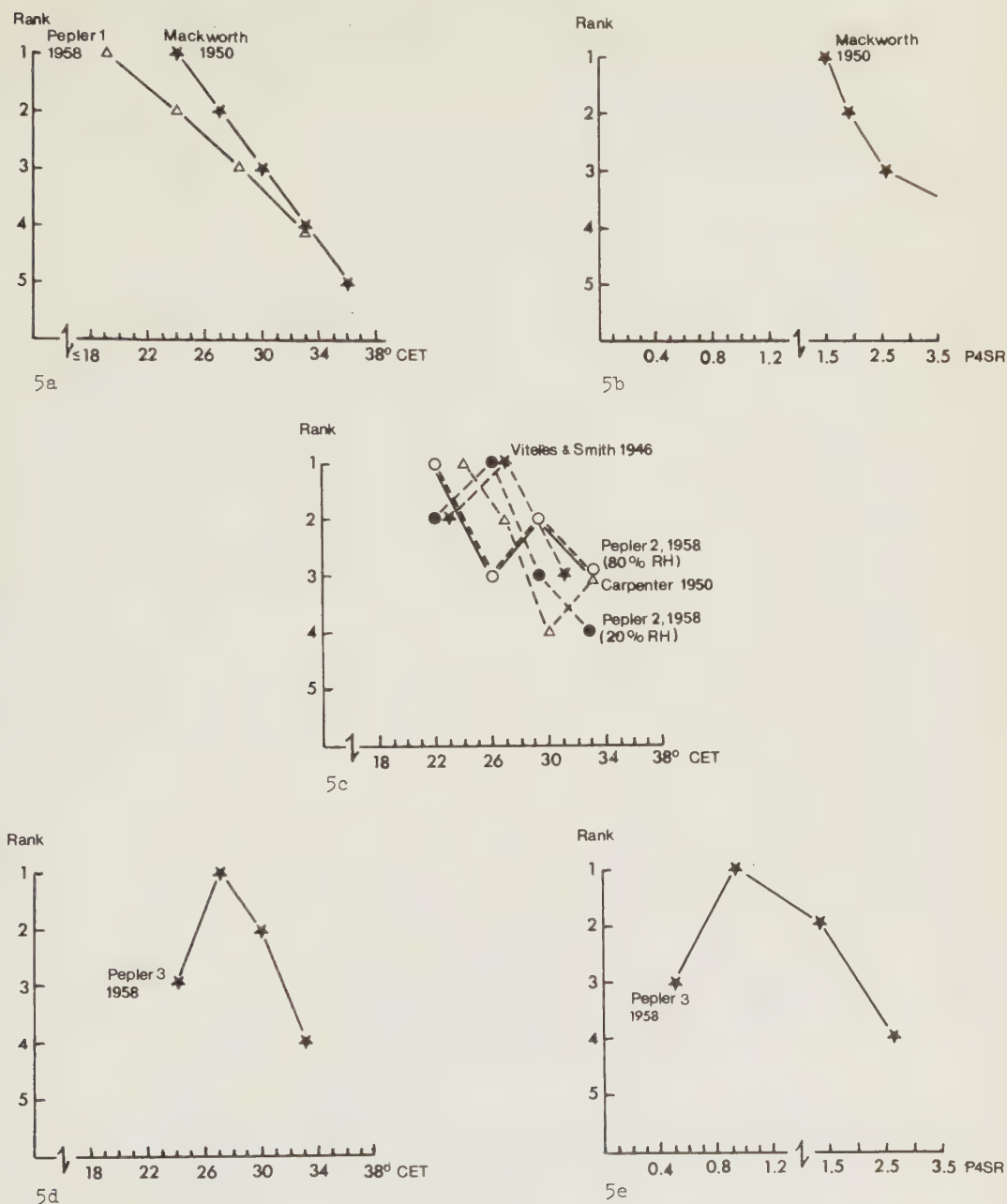


Figure 5. Linear (5a,b), tentatively linear (5c), and curvilinear (5d,e) trends between environmental heat—expressed in ET-units (5a,d,e) and P4SR-units (5b,e)—and perceptual and motor performance (rank 1 denotes optimum performance).

1. Viteles & Smith (1946)

(see above, Mental tasks: linear trend), studying one hour of tracking in addition to a number of other tasks, reported a statistically significant reduction in output at 31° compared with 27° and 23°C ET, whereas the two lower temperatures did not differ. Therefore the trend was tentatively considered linear, as Figure 5 c shows.

2. Griffiths & Boyce (1971)

(see above, Mental tasks: not statistically significant results), in a study of performance and thermal comfort, found a reliable temperature effect on a tracking task when this was performed in combination with a decision-taking task, but not when it was performed alone. The mean tracking score at 21°C ET was worse than at any other temperature, but the difference was statistically significant only between 21°C ET and the lower temperatures—14°, 17°, and 19°C ET—and not between 21°C ET and the next higher one, 23°C ET.

Low but significant negative and linear coefficients of correlation ($r = -.27^*$) were found between tracking and room temperature. Tracking and comfort assessment were not associated.

3. Mackworth (1950)

heat exposed and acclimatized ten 21-30-year-old naval men and also trained them on a heavy pursuitmeter task, before testing their tracking performance during a 3-hour exposure at basic effective temperatures of 24°, 27°, 30°, 33°, and 36°C—erronously reported at higher normal values by Mackworth—as the subjects were dressed in shorts. The pursuitmeter handle weighed about 23 kg; therefore the physical work can roughly be estimated at 170 kcal/h/m². The air velocity was 0.5 m/sec; thus the P4SR-values of the five conditions would be

approximately 1.5, 1.9, 2.6, 4.6, and > 6 .

The failure rate increased logarithmically with an increase in heat load (Figure 5 a, b), and this trend was more marked the longer the exposure. On the basis of the theoretically derived relation:
 $\log \text{ tracking performance} = .9172 + .1794^{\circ}\text{F (dry bulb)}$,
 Mackworth calculated that, compared with the lowest temperature, 24°C ET , the heat had to be raised to at least 30°C ET (corresponding to about 2.5 P4SR) in order to obtain a statistically significant performance deterioration.

Mackworth's pioneer study on tracking has been duplicated and validated by other researchers in the Cambridge group; these studies are reviewed next.

4. Carpenter (1950),
 comparing the influence of handle load and of unfavourable atmospheric conditions, exposed twelve 20-23-year-old, artificially heat acclimatized, naval ratings in a latin square design, to the four lowest basic effective temperatures used by Mackworth, i.e. 24° , 27° , 30° , and 33°C . After one hour of acclimatization, the subjects worked for about one hour on the pursuitmeter at which six different lever loads were tested (0.9, 3.6, 7.2, 10.8, 14.4, and 18 kg; on the basis of other data published by the Cambridge group, these handle loads would, at a rough estimate, correspond to work rates of 70, 82, 117, 132, and 150 kcal/h/m², respectively). This design with varying physical load during each exposure prevents the P4SR-values from being calculated.

Carpenter's results agreed with Mackworth's, implying that the tracking performance was impaired at 30° compared with 37°C ET , whereas the difference between either the two lowest or the two highest temperatures was statistically significant (Figure 5 c; Table 9).

Furthermore, it was found that an increase in the handle load above 3.6 kg adversely influenced the tracking performance. An increase in the handle load amounting to 9 kg—according to the present author's calculations corresponding approximately to a gain in the work rate of 50 kcal/h/m^2 —resulted in approximately the same performance deterioration as a rise of 6°C ET in the room temperature. However, the interaction between handle load and environmental temperature was not statistically significant, although there was a weak tendency for the effect of physical load to be greater at more severe thermal load.

Both body temperature and sweating rose steadily with an increase in ambient temperature. Tracking performance correlated ($r=.35^*$) with body temperature, but was not associated with weight loss due to sweating. Despite these reliable facts, and without presenting any new ones, Carpenter concluded: "It is likely that, such as it is, this correlation is entirely due to the common factor of room temperature, and that there is no direct relationship between performance and either body temperature or rate of sweating. Although the figures from this experiment are far from sufficient in themselves to decide this point, such repeated negative findings suggest that the deterioration in performance is related to room temperature via some mechanism which does not involve a change in such physiological conditions as body temperature or rate of sweating."

Comments: Unfortunately, Carpenter did not hint at the type of mechanism he was thinking of—a centrally or peripherally located physiological or psychological mechanism.

Nor did he comment on the absence of a reliable interaction effect between handle load and environmental temperature. Probably this was because

the subjects worked for only nine minutes (3x3 min trials) at each weight, and the weights were given in randomized order, implying that the interaction effect might have been confounded with aftereffects.

5. Pepler (1958)

during his stay at Singapore, also duplicated Mackworth's study, but Pepler's procedure differed in some respects from Mackworth's. The sixteen naturally heat acclimatized military men at Singapore were, according to a latin square design, exposed to four basic effective temperatures: 19°, 24°, 29°, and 33°C for 160 minutes in each climate. The work rate varied during the exposure and was 82 or 117 kcal/h/m², which makes it impossible to calculate the heat load in P4SR-values.

The results confirmed Mackworth's study. The mean error score in the two coolest climates—which did not differ—each differed from the mean error score in the two warmest climates—which did not differ either (Figure 5 a; Table 9).

An analysis of different error scores, reflecting the tracking behaviour of the subjects, showed that the subjects failed to "keep up" with the requirements of the task. At 29°C ET, both a) lagging behind and b) leading errors increased compared with 24°C ET; and the further increase occurring at 33°C ET for lagging behind errors was also statistically significant, whereas the leading errors decreased at 33°C compared with 29°C ET.

The increase in absolute measures of total sweat loss and rectal temperature was linear and significant from climate to climate; the total sweat loss was 1.7 kg and the rectal temperature was 37.8°C at 33°C ET. However, median test analyses of the relation between absolute readings of final rectal temperature

and total error score indicated that these measures were not associated.

Comments: Unfortunately, no simultaneous readings of physiological and psychological processes were made, nor were analyses of the subjects' deviations under heat load from their normal levels in these respects. Thus the possibility of a reliable and causal relation between change of rectal temperature and change of tracking performance cannot be excluded.

In addition to duplicating Mackworth's study, Pepler performed two other tracking experiments at Singapore. In the first, he intended to make a preliminary test of the effective temperature scale against performance criteria, and similar to Carpenter, also to study the effects of different handle loads (3.6, 7.2, 10.8, and 14.4 kg, which as stated above, at a rough estimate, correspond to work rates of 82, 102, 117, and 132 kcal/h/m², respectively). Four different basic effective temperatures were studied—22°, 26°, 29°, and 33°C—at relative humidities of 20% and 80%. Thirtytwo men were exposed to all eight climates. The P4SR-values of these cannot be stated because the physical work rate varied. After one hour at rest in a climate, the subject spent 90 minutes in the climate chamber tracking and resting in 3-minute cycles.

Statistically significant differences in tracking performance appeared as a function of changes in the effective temperature. The accuracy of tracking declined at 29°C ET, when the relative humidity was low, 20%, but even at 26°C ET in moist climates with 80% RH (Figure 5 c; Table 9). These results—implying that the temperature effect was more marked in moist than in dry climates and the fact that Pepler remarked that the humidity-induced effect on performance "was quite large and almost significant"—tentatively

indicate that the ET-scale is not valid against performance criteria.

The physiological measures of strain also invalidated the ET-scale, because at 26° and 29°C ET, both the average final rectal temperature and the average total sweat loss were higher in dry climates than in moist. None the less, most subjects found it harder to work in the hot-moist climate than in the hot-dry one. The two physiological measures of strain rose with each increase in ambient temperature and amounted to 37.9°C and 1.7 kg, respectively, at 33°C ET. Non-parametric median testing of the relation between final body temperature and total error score was not statistically significant, but irrespective of room temperature, there was some association between the variables in most analyses. In contrast to Carpenter, Pepler reported a statistically significant interaction between ambient temperature and handle load, implying a reliable decline in tracking accuracy with the heaviest load (14.4 kg) at 33° compared with 29°C ET, but with the optimum load of 7.2 kg, the same temperature difference resulted in a performance improvement.

In the third tracking experiment at Singapore, Pepler compared the effects of incentive and speed of work with the effects of room temperature. The high and low incentive conditions were designed in accordance with a previous study by Mackworth (1947; reviewed next). Sixteen male subjects dressed in shorts and sandals were exposed to 24°, 27°, 30°, and 33°C ET, for about 150 minutes: about 75 minutes devoted to tracking and the other 75 to pauses for change of incentive and apparatus. Because the handle load was 7.2 kg, giving a roughly estimated work rate of 102 kcal/h/m², the P4SR-value of the four conditions—including the physical load—would be approximately 0.5, 0.9, 1.4, and 2.6, respectively. Before the main experiments, the subjects had one week of practice on the pursuitmeter

under the two incentive conditions and at four different tracking speeds.

An inverted U-shaped relation appeared between tracking accuracy and environmental warmth. Irrespective of incentive and speed, optimum performance was achieved at 27°C ET—0.9 P4SR—a condition differing from both 24°C and 30°C ET (Figure 5 d, e; Table 9).

Apart from the curvilinear trend, the results agreed with those previously obtained by Mackworth, implying that despite the tracking performance with high incentive in all climate conditions being far better than with low incentive, the environmental effect was independent of the incentive. On the other hand, Pepler emphasized that the adverse effects of thermal load in a specific climate could be overcome—at least for short periods of work under heat exposure—by giving the subject informative feedback and praise.

In contrast to the curvilinear trend appearing with respect to tracking, the sweat loss increase was statistically significant with each increase in environmental warmth (rectal temperature data were not presented). Therefore Pepler concluded that sweat loss and tracking were not associated (for comments on this conclusion see below, Statistical techniques for analysis of the relation between physiological strain and performance changes).

6. Mackworth (1947),
in an investigation of high incentives versus hot and humid atmospheres in a physical effort task, studied how heat **influences motor (not perceptual and motor)** and motivation processes. He exposed thirty male subjects—heat acclimatized and trained on the arm ergograph—to a normal effective temperature of 16°C and to five different basic effective temperatures: 18°C, 24°C, 27°C, 30°C, and 33°C (erronously reported as

higher normal values). The work rate amounted to 310 kcal/h; thus the P4SR-value of the climates would be approximately <0, 0.9, 1.5, 1.9, 2.5, and 4.6. After one hour of exposure in the climates, which were randomly presented on two successive days, the subject worked at a paced rate on the arm ergograph until he was completely exhausted. On one day, the task was administered under high incentive conditions: a) the subject was presented a target value 25% higher than his previous best score, b) informative feedback and encouragement was given; on the other day the task was administered under ordinary conditions.

It was found that high motivation *per se* could not counteract the adverse effects of heat, even if the average amount of work done under all high incentive conditions was superior to work done under ordinary incentive conditions. However, this difference became smaller the more serious the thermal load and was not statistically significant at the two highest temperatures. Actually, the absolute loss of tracking performance was slightly larger when the subjects were strongly motivated, as indicated by the performance under high incentive conditions at 33°C ET—4.6 P4SR—being almost equivalent to the work done under ordinary incentive conditions at 16°C ET, i.e. <0 P4SR. However, the proportional loss of output with and without informative feedback and praise was the same. Otherwise, the work done under both conditions continuously declined and at 27°C ET—1.9 P4SR—was worse than at the coolest climate, 16°C ET. The performance at 27°C ET was in turn better than at the warmest climate, 33°C ET.

The absolute effects of both environmental warmth and incentive were greater for "good" subjects than for "average" subjects, but the proportional adverse effect of heat was approximately the same for the two groups in both instances.

The finding that the most able men were most adversely affected seems to contradict later results by Mackworth (1950) with respect to the Clock Test and morse code reception (see above, Perceptual and non-motor tasks: linear/curvilinear/trend). According to Mackworth, the results are concordant, because they are explicable in terms of the same reasoning. This reasoning suggests that the effects of heat stress on performance are most marked when the subject is working at the best of his ability, strenuously using his resources of energy to the utmost. This was valid both with the "good" subjects working on the arm ergometer, with the inexperienced non-look-outs on the Clock Test, and with the "competent" and the "very good" wireless operators.

Perceptual and motor tasks	°C ET
Linear trend	
Tracking (error score)	
Mackworth 1950	6:24-30
Pepler 1958:exp 1	5:24-29
Pepler 1958:exp 2 (80%RH)	4:22-26
Pepler 1958:exp 2 (20%RH)	3:26-29
Carpenter 1950	3:27-30
Tracking (output)	
Viteles & Smith 1946	4:27-31
Tracking (time score)	
Griffiths & Boyce 1971:central task	2:19-21
Curvilinear trend	
Tracking (error score)	
Pepler 1958:exp 3	3:27-24 27-30

Table 9. Studies of perceptual and motor performance under heat stress yielding statistically significant results ($p < 0.05$) interpreted to indicate a linear or curvilinear relation between heat stress and psychomotor performance. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature.

Conclusions: The reviewed studies, with the exception of the extraordinary finding of Griffiths & Boyce, which as they emphasized "stands in need of replication", indicate that tracking performance, similar to performance on mental tasks and on perceptual-and-non-motor tasks, is probably impaired by environmental heat exceeding about 29°C ET. The critical zone ranges 4°, i.e. from 25° to 29°C ET.

Mackworth's study on a physical effort task indicates that the decline of tracking performance depends not only on perceptual processes, but also on motor processes. Introduction of high incentives might offset the adverse effect on the performance appearing under low incentive conditions in a specific climate, but high incentives might not counteract the declining trend of performance when the heat load is successively increased.

Perceptual and motor tasks: significant results: no trend

1. Bursill (1958)
2. Chiles *et al.* (1972)
3. Azer *et al.* (1972)
4. Pepler (1959 b)
5. Pepler (1960)
6. Poulton *et al.* (1974)
7. Viteles & Smith (1946)
8. Weiner & Hutchinson (1945)

Similar to all studies of perceptual and motor performance reviewed above, most studies comparing only two climates have used some sort of pursuitmeter apparatus. Table 10 summarizes the results of these studies.

Perceptual and motor tasks	$^{\circ}\text{C}$ ET
Tracking (error score)	
Bursill 1958:exp 1:central task	17:18-35
Bursill 1958:exp 2:central task	17:18-35
Chiles et al. 1972:central task	17:19-36
Pepler 1959 [*]	15:18-33
Pepler 1960 [*] : exp 1	15:18-33
Azer et al. 1972:central task	11:21-32
Tracking (time score)	
Poulton et al. 1974 [*] : central task	15:18-33
Tracking (excessive movements)	
Pepler 1959 ^b [*]	15:18-33
Pepler 1960 [*] : exp 1	15:18-33
Serial choice (error score)	
Pepler 1959 ^b [*]	15:18-33
Poulton et al. 1974 [*]	15:18-33
Serial choice (time score)	
Pepler 1959 ^b [*]	15:18-33
Poulton et al. 1974 [*]	15:18-33
Serial choice (variability score)	
Viteles & Smith 1946	8:23-31
Motor-co-ordination (error score)	
Weiner & Hutchinson 1945	15:18-33
Motor-co-ordination (time score)	
Weiner & Hutchinson 1945	15:18-33

Table 10. Studies of perceptual and motor performance under heat stress yielding statistically significant results ($p < 0.05$) without indicating any trend in the findings. The right column presents the minimum reliable difference in effective temperature between the optimum temperature (stated first) and any other adverse temperature; asterisk (*) denotes experiments on interaction between heat and other stresses.

1. Bursill (1958)

(see above, Perceptual and non-motor tasks: significant results: no trend), in two experiments with reliable temperature effects on peripheral vision (Table 7), reported that the errors on a central tracking task were more at 35° than at 18°C ET, and the thermal effect appeared already during the first four minutes of tracking. Unfortunately, the technique of statistical testing did not allow the significant temperature effect to be generalized to a population outside the

sample tested.

2. Chiles *et al.* (1972)

(see above, Mental tasks: significant results: no trend), studying the combined effects of altitude and high temperature, also used a pursuitmeter as a central task in combination with three monitoring tasks. Reliable main effects of the environmental conditions were established. The tracking performance was best in the temperature condition (36°C ET) compared with both the altitude condition and the temperature plus altitude condition when the tracking was worst. None the less, the vertical tracking error for the first 15-minute period in the temperature condition was greater than during the 15 minutes of post-exposure at normal room temperature.

Comments: The findings indicated that even if the temperature effect was comparatively small, it appeared immediately or after a short period of thermal load. However, because a great number of pairwise comparisons were made, it cannot be precluded that the statistically significant difference between the initial exposure and post-exposure period was due to chance factors. On the other hand, it should be noted that the technique of analysis was conservative as the tracking score for the 15-minute period of post-exposure was a negatively biased estimate of the subject's habitual level of performance. Physiological and psychological aftereffects of the exposure period might have influenced the subject and confounded the analysis.

3. Azer *et al.* (1972)

(see above, Perceptual and non-motor tasks: not statistically significant results) also studied central tracking in combination with peripheral lights and reported a reliable temperature effect on the accuracy of alignment at 32°C, but not at 29°C and 31°C ET. Two

interesting findings were:

a) The thermal effect appeared already during the initial 15 minutes of exposure, in agreement with the results of Bursill and of Chiles *et al.*

b) The climate causing impaired tracking was the only one at which a reliable rise in rectal temperature was noted.

Comments: In view of the findings regarding the relation between ability and heat-induced decline in physical work reported by Mackworth (1947), it is interesting to note that the best tracking achievement in the control condition was found for the adversely affected subjects. If their low error score implied that they worked at the top of their ability already at the reference temperature, they could only become worse when exposed to heat. This suggestion is presented as a tentative explanation of the failure of the temperature effect to appear at 29°C ET, which could be expected from the Pepler's Singapore experiments.

4. Pepler (1959 b),
in a classical study of the interaction between stresses, investigated the effects of warmth and sleep deprivation on pursuit-tracking and on a serial choice task. Twelve 18-25-year-old practised naval men performed the tracking task during the initial 30 minutes of each session, and then went on with the serial choice task for the following 20 minutes. All subjects experienced the four experimental conditions obtained by combining one night's lack of sleep, and sleep, with two ambient temperatures, 18°C normal, and 33°C basic effective temperature. As no information was given about the pursuitmeter handle load or work rate, the P4SR-values of the thermal conditions cannot be stated.

As soon as the subjects began work, both tracking

efficiency and the number of pauses on the serial choice task were adversely affected by both heat load and sleep deprivation. These adverse effects then progressively increased.

The two stresses influenced the subjects perceptual and motor performance in different ways. When tracking under heat load at 33°C ET, the subjects tried to correct themselves, as reflected by a statistically significant increase in excessive movements compared to 18°C ET; whereas after sleep deprivation, they tended to move the handle less. For the serial choice task, a reliable increase in the number of faulty responses was found in warmth, but not after loss of one night's sleep. On the other hand, the decrease in the number of correct responses was significant with lack of sleep, but not in heat. On account of these results and because no interaction between, or addition of, effects appeared, Pepler concluded that the effects of heat and loss of sleep depended on different mechanisms. Sleep deprivation was suggested to be dearousing and to make the subject less responsive, whereas the question of the localization and the nature of effects of heat was not answered.

5. Pepler (1960),

in another study of the interaction between stressors, compared the effects on tracking of warmth at 33°C basic effective temperature, glare from a naked 100 W lamp, and noise in terms of quiet but interesting speech. As in the previous study, the cool reference condition had a normal effective temperature of 18°C . In a first experiment, 12 sailors faced the four conditions obtained by combining cool and hot rooms with glare and no glare; and in a second experiment, a further 12 sailors were exposed to the four conditions obtained by combining high and low ambient temperatures with noise and quiet. All subjects, between the ages of 18 and 25 years, were given extensive

practice before the main experiments. The tracking task was given for 40 minutes at each session. After 10 minutes of tracking, glare or noise were added for 20 minutes to the heat stress.

In the second experiment, the effects of heat were confounded with transfer or learning effects from day to day, whereas the results of the first experiment verified previous findings. All three stressors caused a significant decrease in the tracking accuracy, but they differed with respect to change in tracking behaviour. In heat at 33°C ET, a reliable gain in the number of corrective tracking movements was found, in contrast to significant reductions in glare and noise. The results thus indicated that the number of tracking errors under heat load increased probably as a function of an impaired ability to co-ordinate sensory and motor processes. According to Pepler, glare and noise, on the other hand, "interfered with perception of alignment errors".

6. Poulton *et al.* (1974)

(see above, Perceptual and non-motor tasks: significant results: no trend), in the study of the interaction of the loss of a night's sleep with mild heat, **confirmed** the findings with respect to tracking and serial choice previously reported by Pepler. The average percentage of time on target was lower at 33°C than at 18°C ET and decreased progressively. Even if the temperature conditions did not differ during the first 16.5 minutes of tracking, as was the case in Pepler's investigations, the difference during the following 16.5 minutes was reliable. This trend was more marked when heat was combined with sleep deprivation. However, in agreement with Pepler's findings, no reliable full time interaction was found between heat and loss of sleep, either for tracking or for serial choice.

In the serial choice task, the interaction over time changed in the opposite direction, but it was reported to be statistically significant only with regard to error percentage, i.e. at the beginning, the adverse effect of lack of sleep and heat *per se* was larger than the combined effect, whereas at the end, the reverse was valid. Although these different interaction patterns over time are not fully understood, Poulton *et al.* emphasized them and "the need to consider task variables more seriously than is usually done in stress experiments." Moreover, it is to be noted that both sleep deprivation and warmth increased full time scores for error percentage and pauses.

7. Viteles & Smith (1946),
(see above, Mental tasks: linear trend) studying serial choice performance under heat load, reported a statistically significant temperature effect on the variability score.

8. Weiner & Hutchinson (1945),
in three experiments, studied the effects of heat on the performance of a motor co-ordination (sorting) task. Because no statistical testing was made either in the first experiment on four subjects or in the third experiment on prolonged heat exposure of one subject, only the second (main) experiment will be reviewed. Six heat acclimatized and practiced 25-35-year-old subjects were exposed to 18° and 33°C normal effective temperature. First, they carried out a physical effort task (step climbing) for 2 x 10-minute periods, resulting in a rise in body temperature to about 38.3°C. After one hour's rest, the pulse rate was stabilized, and they performed the motor co-ordination task.

Both speed of work and accuracy were influenced by the heat at 33°C ET. Under thermal load, the subjects worked more slowly and made more errors.

Comments: A suggestion by Weiner & Hutchinson that no relation exists between absolute readings of rectal temperature and performance was confirmed by the present author, who carried out an analysis of regression and correlation on the raw data presented in the original paper.

Conclusions: In the last reviewed studies, most of which have investigated the interaction between heat and other stresses, the findings agree well with the previous conclusions that an ambient temperature exceeding 30°C ET probably causes a reliable decline in psycho-motor performance. However, as the warmest climates investigated in these studies have mostly exceeded 30°C ET, the possibility of a performance deterioration even below this value is not precluded. In particular, it can be expected that more complex perceptual and motor tasks than tracking or serial choice are adversely affected at lower room temperatures.

This was found in a paper by Wyon (1973), who re-analysed data from four extensive experiments on the effects of heat on type-writing performance, previously reported by the New York State Commission on Ventilation. Using non-parametric statistical methods, Wyon found a reliable decline in type-writing at 24°C and 50% RH compared with 20°C and 50% RH for subjects attending the experiments for seven hours a day for at least one week (data about air speed was not given, so ET-values cannot be calculated).

In most studies, the adverse effects of heat on psycho-motor performance have occurred very soon. This tentatively indicates that heat, besides causing a conceivable fatigue effect which increased progressively with the exposure duration, also reorganized the behaviour of the individual. In most studies, no relation has been found between body

temperature and performance; therefore it seems though the reorganization of behaviour should not be based on the functioning of the thermoregulatory system but on some other—perhaps psychological—mechanism. Actually, in a study of a difficult tracking task performed in extreme warmth at 43°C ET, Pepler (1959 a) concluded, in view of immediately increased tracking movements and at first unaffected accuracy of alignment, "that extreme warmth may act as a powerful incentive". By which he meant that the heat acted as a challenge to which the subjects responded with high ambition to withstand the thermal load and make a good run. Apparently, they did not succeed, because the tracking errors increased rapidly and progressively.

Unfortunately, Pepler did not report any statistical testing of his findings. Moreover, it is not evident that what might be valid for extreme warmth is also valid for moderate heat stress. None the less, if moderate heat operates on psychomotor tasks, not via the thermoregulatory system but via some psychological mechanism, the nature of heat stress effects on perceptual and motor tasks apparently differs from the nature of heat stress effects on perceptual and non-motor tasks. This conclusion is supported by the trend in the data for most studies of perceptual and non-motor tasks being curvilinear (Figures 3, 4), whereas the trend was linear in most studies of psycho-motor tasks (Figure 5).

Another fact that might explain the different trends is that, in most studies of psycho-motor performance, the subjects have been heat acclimatized, whereas this was so in only half of the studies of perceptual and non-motor performance. The thermoregulatory function of heat acclimatized subjects differs from unacclimatized subjects (Leithead & Lind 1964, pp.16-30). Provided performance is dependent on the

thermoregulatory function, different results are to be expected for heat acclimatized and unacclimatized subjects (cf. above).

It should be noted that none of the studies of perceptual and motor performance were carried out under induced hyperthermia. Until such a study is performed, the dependence of psycho-motor performance on physiological and/or psychological mechanisms is equivocal.

Perceptual and motor tasks: not statistically significant results

1. Bursill (1958)
2. Chiles *et al.* (1972)
3. Viteles & Smith (1946)
4. Pepler (1959 b)
5. Poulton *et al.* (1974)
6. Griffiths & Boyce (1971)
7. Colquhoun & Goldman (1972)

As was the case for several studies of perceptual and non-motor tasks, some investigations of psycho-motor performance have yielded both statistically significant and not significant results for different measures of the same task. Table 11 lists studies reporting not statistically significant results.

Perceptual and motor tasks	^o C	ET
Tracking (error score)		
Bursill 1958: exp 3:central task	17:18-35	
Chiles <u>et al.</u> 1972: central task	17:19-36	
Chiles <u>et al.</u> 1972*: central task	17:19-36	
Viteles & Smith 1946	8:23-31	
Tracking (time score)		
Griffiths & Boyce 1971: single task	9:14-23	
Tracking (excessive movements)		
Bursill 1958: exp 1:central task	17:18-35	
Bursill 1958: exp 2:central task	17:18-35	
Bursill 1958: exp 3:central task	17:18-35	
Tracking (total activity score)		
Bursill 1958: exp 1:central task	17:18-35	
Bursill 1958: exp 2:central task	17:18-35	
Bursill 1958: exp 3:central task	17:18-35	
Tracking (variability score)		
Viteles & Smith 1946	8:23-31	
Serial choice (output)		
Viteles & Smith 1946	8:23-31	
Serial choice (correct choices)		
Pepler 1959 b*	15:18-33	
Poulton <u>et al.</u> 1974*	15:18-33	
Simple reaction time		
Chiles <u>et al.</u> 1972: peripheral task	17:19-36	
Chiles <u>et al.</u> 1972*: peripheral task	17:19-36	
Choice reaction time		
Chiles <u>et al.</u> 1972: peripheral task	17:19-36	
Chiles <u>et al.</u> 1972*: peripheral task	17:19-36	
Meter monitoring (time score)		
Chiles <u>et al.</u> 1972: peripheral task	17:19-36	
Chiles <u>et al.</u> 1972*: peripheral task	17:19-36	
Hand steadiness		
Colquhoun & Goldman 1972	<u>1.0:37.6-38.6</u>	

Table 11. Studies of perceptual and motor performance under heat stress yielding not statistically significant results. The right column presents the largest not significant effective temperature difference between the optimum temperature (stated first) and any other adverse temperature; underlined values refer to body temperature; asterisk (*) denotes experiments on interaction between heat and other stresses.

1. Bursill (1958),

(see above, Perceptual and non-motor tasks: significant results: no trend) reporting a reliable temperature

effect on tracking efficiency in his first two experiments with high tracking speed (Table 10), did not find any heat-induced increase in the error score in his third experiment, when the tracking speed was slow. Nor were number of excessive movements or total activity score affected at 35°C ET in any of the three experiments.

2. Chiles *et al.* (1972),

(see above, Mental tasks: linear trend) in a study of the combined effects of altitude and high temperature on tracking, found no change of error score in the temperature plus altitude condition, whereas in the temperature condition, vertical tracking errors increased during the first 15-minute period in heat (Table 10) but not during the second period; horizontal tracking errors did not change at all. None of the three secondary tasks—simple reaction time, choice reaction time, and meter monitoring, concurrently executed with tracking, was influenced when the room temperature was increased 17° (from 19° to 36°C ET).

3. Viteles & Smith (1946),

(see above, Mental tasks: linear trend) reported that the measures of both tracking efficiency and tracking variability remained almost unchanged, although the room temperature exceeded 30°C ET, and the measure of output was impaired (Table 9). However, on the serial choice task, the output score did not change, but the fluctuation in the amount of work done increased under heat load (Table 10).

4. Pepler (1959 b)

5. Poulton *et al.* (1974),

investigating the interaction between heat and other stresses, did not find any reliable change in the number of correct choices on a serial choice task in

which both error and time scores were adversely affected at 33°C ET (Table 10).

6. Griffiths & Boyce (1971), (see above, Mental tasks: not statistically significant results) reporting a decreased time on target when tracking was carried out at 21°C ET as a central task in combination with decision taking (Table 9), did not find any temperature-induced influence on alignment when tracking was given singly.

7. Colquhoun & Goldman (1972) reported that, although some subjects showed a noticeable body sway due to induced hyperthermia, tests of hand steadiness did not differ from the mean value under control conditions.

Conclusions: In summary, the reviewed findings confirm the previous conclusion concerning perceptual and non-motor performance that the crucial factor for heat-induced performance changes is not the type of task but the measure of performance. For a specific psycho-motor task, the time score that measures physical work rate can be unaffected both within and at comparison between climates, whereas at the same time, the error score is adversely affected. This means that, although the subject can continue to work, his ability to work efficiently is reduced; thereby the risk of accidents is increased to a corresponding degree.

The results have tentatively indicated that the more severe the task load, the greater the probability of a heat-induced performance decrement.

The seemingly large average effective temperature difference between climates that cause no impairment of psycho-motor performance is not to be taken as evidence that the ambient temperature might be raised

at least 15°C from an ordinary level before it influences performance. The large difference is an artifact, depending on most studies of psycho-motor performance having investigated only two climates.

Previously, it was suggested that differences in trend between perceptual-and-non-motor and psycho-motor tasks could be explained by differences in heat acclimatization of the subjects in different studies. However, statistically significant and not significant results for psycho-motor tasks cannot be explained by differences in acclimatization, because most subjects in the reviewed studies of psycho-motor performance have been acclimatized.

Conclusions based on the review

The reviewed studies show that the heat stress research into human performance dealt with many different problems during the past 20 years. Mental, perceptual, and psycho-motor tasks were studied almost exclusively in laboratory experiments performed on heat acclimatized fit young men. In most studies, the subjects were given extensive practice on the performance tasks, which thus were well learnt before any heat exposure took place. The exposure time varied from less than one hour to several hours, but the exposure duration seldom exceeded three hours. Only exceptionally were subjects studied in experimental series with repeated exposures over periods of more than a few days.

The emphasis recently shifted from an exploration of the relation between constant ambient temperature and performance to studies of performance changes under controlled hyperthermia or during ambient temperature swings. Unless otherwise stated, the presented conclusions are based on studies of constant ambient

temperatures, which are probably preferable to a varying indoor climate for normally dressed subjects performing sedentary mental work.

Unfortunately, most studies describe the climatic conditions in terms of the ET-scales. Information about air speed and the subject's clothing are not always reported, and data about work rate are almost completely lacking. Therefore it is impossible to compare the validity of the ET-scales and the P4SR-index as intended. The practice of expressing thermal load in terms of scales based on assessments of thermal sensation (ET-scales) instead of on bodily reactions and physiological strain (P4SR-index) has created some doubt about what heat stress actually is. In some investigations, headed heat stress studies, the subjects were exposed to subjectively as well as physiologically thermally neutral conditions or even to conditions that caused not a bodily heat gain but a heat loss (e.g. Ryd 1970, Griffiths & Boyce 1971).

Based on the reviewed studies, it can be concluded that an ambient temperature exceeding 30°C ET will probably impair the performance of mental, perceptual, and psycho-motor tasks for subjects stripped to the waist. A critical zone probably exists between 27° and 30°C ET, suggesting that, in certain situations, the performance of some tasks will be impaired even below 30°C ET, but not below 27°C ET.

There does not appear to be any general relation between ambient temperature and performance change, although in most studies of mental tasks, a linear relation has been found, whereas for perceptual but non-motor tasks, a curvilinear relation has appeared. The curvilinear trend indicated that an optimum performance was achieved in the temperature interval $24^{\circ} - 27^{\circ}\text{C}$ ET. In contrast to mental and perceptual-and-non-motor tasks, no clear relation was found

between heat and psycho-motor performance; therefore the tentative suggestion that the nature of heat effects on perceptual performance differs from the effects on psycho-motor tasks.

The fact that statistically significant results were obtained for some measures of a specific performance task, whereas other measures of the same task were not influenced indicates that what is relevant in the selection of performance tasks is not their structural but their functional and dynamic characteristics.

Although previous studies often reported an absence of any causal relation between body temperature and performance, recent studies making use of the more refined technique of inducing hyperthermia definitely showed that performance changes under heat load are dependent on body temperature. It must now be considered established that body temperatures above 38°C affect most types of performance. However, the nature of the functional interrelation between heat stress, strain, and performance is not yet clarified. This is because most studies were undertaken to solve practical problems of work in industrial, military, and educational settings. Theoretical approaches in the field of heat stress are rare.

Concerning the relations between performance and measures of physiological strain other than body temperature, the available data are too scanty to permit any conclusion other than that more research is necessary before the problem can be solved. Another question to be answered is in what way are different measures of physiological strain related to each other.

As emphasized above, the functional interrelation between ambient temperature, thermoregulation,

physiological strain, and performance are ambiguous. This ambiguity is reflected by the fact that, in some studies, the thermally induced effects on performance appeared with full strength shortly after the subjects were heat exposed, and the effects then remained constant. In other studies, no effects of heat were found initially until they suddenly occurred at the end of the exposure. Finally, some studies reported progressively increasing heat effects on performance. The discordant findings can be referred to differences in design, procedure, apparatus, and selection of subjects. Therefore some standardization in these and other relevant aspects is necessary.

The occurrence of statistically significant results in some studies, but not in others, can be connected with the use of statistical testing. In some studies, no over-all test was made to investigate whether any temperature effect has appeared, the testing being made by means of a large number of nonorthogonal comparisons (e.g. Viteles & Smith 1946, Ryd 1970, Azer *et al.* 1972). This increases the risk of committing a type I error and renders the conclusions of the testing doubtful.

The ambiguity concerning functional relations is also proved by the dispute about whether heat is intrinsically arousing or de-arousing. To some extent, this state of affairs may be related to the fact that measurements of physiological strain were mostly restricted to recordings undertaken at the beginning and end of the heat exposure, instead of a continuous recording.

The review unequivocally shows that a high degree of motivation cannot counteract the adverse effects of heat load on performance. It was also found that subjects working at optimum effort, strenuously using

their final resources of energy, and subjects working at the limit of their ability are most easily adversely affected by environmental warmth.

Although only few studies have considered heat-induced performance changes with regard to personality variables, it can be concluded that the subject's personality structure and dynamics might influence his physiological and psychological reactions under heat load. However, the question of how different personalities are affected remains to be answered.

PROBLEM ANALYSIS

The review definitely bears out the truism that good research raises more questions than it answers. Even if knowledge about the effects of heat on bodily function and performance has increased, a large number of questions remain unresolved. Some old questions also need reformulation in order to be appropriately answered. Figure 6 schematically presents the heat stress research paradigm adopted and the questions to be analysed in this study. They will now be discussed.

Measures of heat stress

As previously stated, one of the fundamental problems in heat stress research is to describe adequately and measure the thermal load of the environment. From a physiological and psychological frame of reference, the stress itself can only be properly defined with respect to either a) the physiologically determined heat production or b) the subjectively reported assessment of environmental warmth. Thus the four climatic determinants: temperature, speed, and humidity of the air, and radiant temperature are not

Question 1: Does heat stress influence physiological function, thermal assessment, and performance?



Does heat stress influence in the same way the performance of subjects with:

high	low	high	low	high	low	high	low	"normal" "deviating"	much adversely	less adversely
physiological strain?		psychological strain?		intelligence?		skill?		personality?		affected subjects?

Question 2.

Question 3.

Question 4.

Question 5.

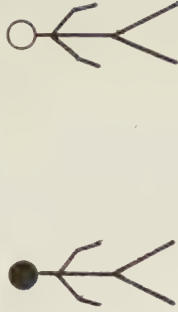
Question 6.

Question 8.

Question 9.

Question 7: Do much and less adversely influenced subjects differ with respect to individual characteristics, and if so, which are these characteristics?

Performance change under heat stress:
much adverse less adverse



Do subjects differ and form subgroups with respect to individual characteristics, and if so, which are the characteristics distinguishing subgroups of:

affected subjects?					

Question 8.

Figure 6. Illustration of the adopted heat stress research paradigm and research questions.

Questions 1-6 are answered by analysis of variance technique; Question 7 is answered by D-index or Q-factor analysis technique; Questions 8-9 are answered by Q-factor analysis technique.

system relevant in biological heat stress research, although they unambiguously describe the physical characteristics of the climate and for this purpose are indispensable. Whatever the values of these parameters are, no biologically meaningful heat stress exists in an empty hot and humid room. Not until an individual enters the room and is affected by the environmental conditions does any thermal stress exist.

At present, the ET-scales are the most commonly used index, whereas the P4SR-index seems to be unsurpassed for description and measurement of the climate stress of the environment. However, besides the empirically found shortcomings of the ET-scales, previously referred to, a theoretical inconvenience of the scales is that they lack an absolute or system relevant zero point as was clearly shown in the review. This means that no natural zero point is given, and it can be hard to decide which ET-value should be chosen as reference or control value. Some investigations use an effective temperature around 18°C to define the control condition, whereas others fix the reference temperature at about 25°C ET. Such a discrepancy in the choice of the reference condition will naturally influence the possibility of obtaining statistical significance at comparison with climates around 30°C ET. Thus the researcher could bias the results by the choice of his control temperature.

This risk is minimized by using the P4SR-index, which has an absolute zero point. The P4SR-value zero means that the expected sweat rate per four hours is nil, and a climate of 0 P4SR does not impose any physiological heat stress on the individual. Because of this advantage of the P4SR-index and because it expresses the ambient heat stress in terms of the degree of physiological strain produced by the heat

instead of in terms of assessments of thermal sensation, it was adopted as the basic measure of heat stress in this study.

Physiological measures of heat strain

When the human body is exposed to heat, several physiological changes are induced. These changes are often completely neglected and are not measured, or are unsufficiently treated.

The physiological changes or strain reactions that occur as a function of thermal stress partly counteract the disturbance of heat balance, for instance sweating and vasodilatation, causing some cooling of the body, are partly themselves caused secondarily by the thermoregulation, for instance increase in heart rate to compensate for vasodilatation, and finally, they reflect the inability of the thermoregulatory system to completely compensate for the thermal load, for instance, rise in body temperature. Thus all the physiological reactions depend on the amount of heat stress besides being interdependent.

The investigation was therefore planned to study not only the compensatory change of sweating, the secondary effect on pulse rate, and the heat gain in rectal temperature under heat exposure, but also the interrelations of these three measures of physiological strain (Figure 6 Question 1). A negative relation was assumed to exist between sweating and rectal temperature, as under heat load, an inadequate thermoregulation results in low sweating and increased rectal temperature, whereas under reference conditions, subjects with a high habitual sweat rate probably have a comparatively low body temperature due to the evaporative cooling

effect of sweating. On the other hand, a positive association was expected between pulse rate and body temperature, as both these measures of physiological strain tend to increase, the more heat-affected the subject becomes.

In order to obtain a description over time of the change of the strain measures, the recording system was designed for repeated time sampling instead of the usual way of making measurements before and after each exposure. This means that intra-subject comparisons could be made with respect to the effects of exposure duration. From a physiological standpoint, it could be hypothesized that a general mechanism of thermoregulation and heat tolerance determines the subject's physiological reactions under heat stress. Thus subjects physiologically affected at the beginning of thermal exposure would be affected at the end too, and those who were affected by moderate heat load would be affected also by more severe heat stress.

Above, it was proposed that heat stress itself acts

- a) directly on the body only by way of the changes in bodily functions that are caused, or
- b) indirectly via the subject's experience of the heat and his interpretation of the physiological changes. These changes are partly controlled by the brain, for instance, sweating is assumed to be under the control of the hypothalamus (Green 1966, p. 96), but they also influence the metabolic rate in the nerve cells in the brain, for instance, the deep or core body temperature (Fusco 1963 a). This means that a direct relation between heat stress—characterizing the climatic conditions of the environment—and performance is less probable, whereas heat strain—reflecting the physiological influence of the ambient

temperature—and performance can be expected to show a close relation.

There is no general agreement about which of the physiological changes is the preferable measure of heat strain. Previous work by Löfstedt (1966) indicated that complete inability or collapse was best predicted by deep or mean body temperature. A number of studies reviewed above also indicate a close relation between performance and body temperature under imposed moderate heat stress (Wilkinson *et al.* 1964, Colquhoun & Goldman 1972, Trygg 1972). The sweat rate ought to be directly related to the amount of heat stress, but as a measure of heat strain, it could be misleading, as a low sweat rate could be a function of either a low heat stress or an insufficient thermoregulation. The pulse rate is strongly influenced by factors other than thermoregulation, for instance, sex, age, physical fitness, personality, and task-induced psychological strain. However, at least within the individual, the pulse rate has been successfully used as a measure of heat strain.

In general, intra-individual analyses of physiological measures could be expected to give more clearcut and consistent results than inter-individual analyses. Unfortunately, no investigation has been found that compares the association between different strain measures, on one hand, and performance on the other. Therefore, it was decided to perform analyses of correlation and regression between performance and all strain measures recorded (Figure 6 a Question 2).

The relation between physiological strain and performance

The analyses of the relation between physiological strain and performance were based on two different

ways of measuring strain and performance; namely, absolute and deviation scores.

Absolute scores, being the usual way of measuring, indicate the actual body temperature, sweating, pulse rate, or achievement recorded. Because a high strain value or a low performance score does not directly indicate that the subject is influenced by the environmental conditions, analyses of correlation and regression based on absolute scores could be misleading or could give insufficient information about the functional relations between heat stress, strain, and performance. High absolute strain values might reflect a habitually high level of physiological functioning, or a high degree of thermoregulatory activity, and low absolute performance scores might represent a low proficiency, or a heat-induced adverse effect on performance. The absence of any statistically significant relation between physiological strain and performance, reported in a number of the studies reviewed above, can be explained in terms of this fact.

The shortcomings of absolute scores are partly circumvented by the use of deviation scores instead of absolute scores. Deviation scores express not only in what direction, but also to what extent, physiological function and performance under heat load diverge from corresponding basal values recorded in a reference climate. Thus deviation scores, which eliminate basic individual differences might be expected to provide more accurate information about heat induced changes than do absolute scores.

However, it should be noted that deviation scores also depend on the subject's habitual level. Under thermal load, the performance of very poor subjects cannot become much worse on some tasks, whereas there might be almost no room for improvement for very good subjects. In this study, the influence of the subject's

habitual physiological level and his habitual level of performance was reduced by separately analysing subjects with high and low basal values.

According to the outlined physiological model, it can be predicted that the higher the physiological strain, the greater the impairment of performance (Figure 6 a Question 2). This prediction is probably most valid for physical and psycho-motor tasks, as the performance on such tasks strongly depends on the body's physiological functioning. A disturbance in thermoregulation forces the body to counteract the upset of heat balance and to use energy in order to reach thermal equilibrium. Thus less energy will remain for mental and, in particular, for physical work, which therefore become more sensitive to the influence of environmental warmth. The predicted relation is expected to be most marked between body temperature and performance, as changes in body temperature directly reflect the inability of the thermoregulatory system to maintain thermal equilibrium.

Psychological measures of heat strain

Previously, it was pointed out that the performance under heat load might be influenced not only by the induced physiological strain but also by the psychological strain. The psychological strain is induced partly by the subject's experience of the ambient heat and by his interpretation of the physiological strain reactions. In that respect, factors outside the experimental situation might also operate. Research on noise has shown that the subject's previous experience of noise, or his attitude to the source of annoyance, can influence his psychological reactions (Cederlöf *et al.* 1961, Sörensen 1970). It seems reasonable to suggest that

the same phenomenon is operating for heat.

Other non-thermal factors acting in the experimental situation might also cause a psychological strain. Such factors could, for instance, refer to the physiological recording devices attached to the subject, or to the performance tasks and the instructions given to the subject. In this last respect, the effort of the subject is an important psychological strain variable. However, as was previously pointed out, it is difficult to measure effort in a reliable and valid way.

In this study, psychological strain refers mainly to the subjects' thermal ratings of the climate conditions (Figure 4 a Question 3). As a high degree of psychological strain probably incapacitates the subject, it was expected that a greater deterioration of performance for subjects perceiving the climate as too warm or even hot, compared with subjects reporting the climate just right, would be found. Furthermore, it seems reasonable to suggest that the effects of psychological strain would be most marked under low or moderate heat. Under more severe heat load, the psychological strain effects on performance will probably be masked by comparatively greater effects of the physiological strain.

Skill and other intervening variables

With respect to skill, it can be predicted, according to previous findings of Mackworth (1947, 1950), that the effects of thermal load would appear most clearly for subjects working at maximum effort even under ordinary climate conditions (Figure 4 a Question 5).

On most tasks, and in particular on well practised tasks, poorly performing subjects would probably

suffer most in heat, as they are required to work at the limit of their ability even in a thermally neutral environment. On the other hand, the performance of good subjects is likely to be more seriously affected by environmental stress on less practised tasks. This is because even good subjects have just learnt how to carry out the task without yet having acquired a well-practised work routine; whereas the poor subjects, trying to develop a strategy for performing the task, cannot get much worse under heat load, the newly formed habits of the good subjects are easily disturbed by any stressful factor.

A fundamental difference is to be emphasized between the two discussed determinants of performance: physiological measures of strain and skill. Skill, defined as the subject's average level of performance, is an individual characteristic that does not depend on environmental factors other than the specific task used for operational definition of the concept. Although skill, for obvious practical reasons, is usually estimated under ordinary environmental conditions, this does not mean that skill, *per se*, is influenced by environmental stressors. What really is affected by environmental warmth or noise, for instance, is rather the subject's ability to make use of his skill, i.e. the potential is not reduced although its availability is. Methodologically, skill could be termed an hypothetical construct with features of an independent variable, whereas the actual performance is a variable that depends on both skill and environmental factors. Other examples of such independent variables, which probably determine the change of the subject's behaviour under heat stress, are general intelligence and personality (Figure 4 a Questions 4 and 6).

The physiological measures of strain differ from skill, intelligence, and personality, as they cannot be dealt

with independent of the thermal stress, as previously emphasized. In fact, they are treated as dependent variables within a physiological frame of reference. At the same time, they must be regarded as intervening variables between the independent variable of heat stress and the dependent variable of performance. Other intervening variables that also might explain changes in performance under thermal load are the subject's level of arousal and effort (Hebb 1955, Bell & Provins 1962, Pepler & Warner 1968, Wyon 1970). These two variables influence not only performance but also the span of attention (Easterbrook 1959) and probably are mutually dependent.

Arousal changes in heat

The level of arousal is usually regarded dependent on all stimuli—internal as well as external—that act on the subject in a given situation (Broadbent 1963 b). The arousing effects of the environmental heat and the motivation produced by the performance task, apart from the subject's habitual arousal, are of particular significance for the study of performance changes under thermal exposure. The environmental heat could affect the level of arousal in at least two ways.

First, in the hypothalamus region of the brain, centres are located for thermoregulation: a heat-loss centre in the anterior hypothalamus and a heat-producing centre in the posterior hypothalamus; for regulation of sleep, the posterior hypothalamus, and for wakefulness, the anterior hypothalamus (Ochs 1965, p. 439, 535). Thus it seems reasonable to suggest that a rise in the hypothalamus temperature due to increased environmental heat would affect not only the hypothalamic thermoregulation, as suggested above, but also the level of arousal. This is undoubtedly

the reason for great changes in environmental temperature, for instance, at cold-induced coma, or at heat syncope.

Because the metabolic rate of all living cells, and consequently the arousal of the nervous system, is temperature dependent, it can be supposed that a rise in the deep body temperature monotonically increases the level of arousal from cold-induced coma to heat cramps, followed by a rapid decrease of arousal and heat syncope (cf. the arousal pattern in epileptic seizure). Conversely, it could be expected that a change of arousal would affect the hypothalamic temperature. Fusco (1963 a), indeed, showed that a change of posture in the resting dog almost immediately increased the hypothalamic temperature, whereas it decreased steadily when the dog slept. She also reported that a change in the hypothalamic temperature altered the dog's behaviour from shivering at low temperatures to panting at high temperatures, although the body temperature was not much influenced (Fusco 1963 b; cf. below, Okuma *et al.* 1965).

Secondly, it should be recognized that the level of arousal is also a function of peripheral stimulation. The neural impulses from the thermoreceptors in the skin influence both the reticular arousal system and the cortex of the brain, thus affecting subconscious and conscious areas.

The human being experiences skin temperature ranging from 29° to 36°C as neutral (Kenshalo 1971), i.e. skin temperatures within this interval do not produce any thermal sensation, and consequently have little effect on the level of arousal, whereas lower or higher skin temperatures are perceived as cool or warm, respectively, probably implying a change of arousal via the cortex. On the basis of these

psychological facts, it could be hypothesized that the relation between skin temperature or afferent impulses from peripheral thermoreceptors and arousal is U-shaped. This hypothesis resembles that of Provins (1966), but differs from his, as it is based on the functioning of peripheral mechanisms instead of central ones or deep body temperature dependent mechanisms (cf. above).

The present hypothesis is supported by the findings of Okuma *et al.* (1965), also referred to by Provins. These researchers reported that the electrocortical activity in cats immobilized by neuromuscular blocking agents was desynchronized when the environmental temperature was much lower or much higher than the rectal temperature, which was measured and maintained around 37°C. The pattern of electrocortical activity was synchronized when the room temperature approached 30°C. Synchronization also appeared at room temperatures below 25°C when hot water bags were placed against the abdomen. The application of cold water bags caused desynchronization, whereas thermally neutral stimuli did not influence the EEG pattern. On the basis of partial and total transections of the neuraxis, Okuma *et al.* concluded that the electrocortical changes depended on the afferent impulses from peripheral thermoreceptors and probably not on alterations in the hypothalamic temperature (cf. above, Fusco 1963 b).

A combination of the two presented hypotheses leads to the conclusion that the level of arousal is not determined by merely central or merely peripheral mechanisms, but by both factors combined. However, the deep body temperature and the skin temperature are probably not of equal importance. Rather they are to be weighted to an organic temperature in a way corresponding to that used for the calculation of mean body temperature. Superimposition of the

U-shaped curve derived from the peripheral mechanism hypothesis on the interverted U-shaped curve derived from the central mechanism hypothesis tentatively gives a relation between arousal and organic temperature, as shown in Figure 7.

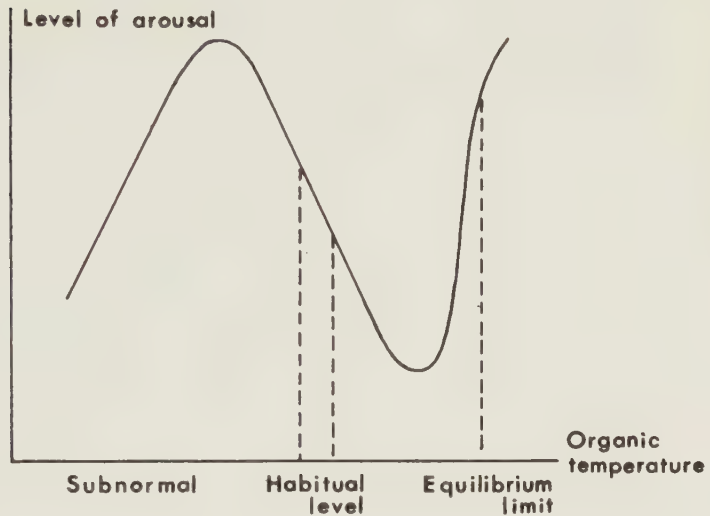


Figure 7. Hypothetical relation between organic temperature and arousal.

The figure clearly illustrates the answer to the debated question whether environmental heat is arousing or dearousing; it is both, depending on the actual temperature of the organism in relation to the ordinary organic temperature. With reference to the figure, some remarks concerning the concept of arousal seem justified.

As pointed out by researchers on arousal (Hebb 1955;

Duffy 1957, 1962), both high and low levels of arousal are conducive to poor performance, i.e. performance shows an inverted U-shaped relation with arousal. At low levels of arousal, the activating impulses to the cortex from the reticular ascending system (RAS) are too scanty to facilitate the neural and synaptic function, so that the behaviour will be properly organized and integrated. This is reflected, *inter alia*, by a reduced psycho-physiological sensitivity and motor activity. When the level of arousal, on the other hand, is high, the flow of RAS impulses might be suggested to be so frequent that irrelevant responses are facilitated. It also seems reasonable to suggest that relevant responses might be inhibited and blocked. The behaviour will therefore be hyperactive, or alternatively, almost paralyzed. This means that a continuous quantitative increase in arousal could be associated with marked qualitative changes in behaviour and sensory function. It would thus be a misunderstanding of the concept of arousal to suppose that only quantitative changes of motor and sensory activity are associated with changes in arousal.

Concerning the relation between arousal and organic temperature, illustrated in Figure 7, it should be noted that an organic temperature somewhat below the ordinary habitual level is supposed to be arousing, as is an organic temperature around the thermal equilibrium limit. The arousing effects of a slightly subnormal organic temperature is reflected by hypothalamus triggered shivering and annoying feelings of cold. At organic temperatures above the equilibrium limit, muscle cramps and signs of aggression and euphoria might appear. Thus the qualitative effects of cold and heat-induced arousal might be quite different. Moreover, performance changes under cold exposure probably depend on a direct peripheral effect on receptors in the skin,

on blood vessels, and on muscles, rather than being a function of changes in arousal.

The relation between arousal and performance changes in heat

The concept of arousal is discussed at length because it seems to be crucial for performance in addition to the physiological strain reactions. According to the outlined psycho-physiological model of arousal and Hebb's arousal-performance model, some interesting predictions can be made with respect to performance changes under heat load.

For tasks requiring an ordinary level of arousal for optimum performance, it can be predicted that the performance will deteriorate at slightly increased organic temperature, as the level of arousal is decreased below its optimum level (Figure 7). However, a big rise in the climate load will cause an impairment due to either too high or too low arousal in combination with strenuous physiological reactions.

At a comparison of performance on two versions of a task—an easy and intrinsically dearousing version and a difficult and arousing version—different heat-induced patterns of change are to be predicted (cf. the Yerkes-Dodson law). The performance on the easy version probably deteriorates almost monotonically when the environmental temperature and the temperature of the organism increases. First, the level of arousal becomes too low, and then it grows too high for optimum performance (Figure 7). On the difficult version, on the other hand, the performance will benefit when the arousal level, being too high under ordinary conditions, is reduced to almost optimum level under moderate heat load. A further increase in load is first too arousing and then too dearousing;

therefore the performance will deteriorate. The relation between heat load, reflected by organic temperature, and performance would thus be linear for the easy version and curvilinear for the difficult one.

According to a hypothesis proposed by Easterbrook (1959), suggesting that "the number of cues utilized in any situation tends to become smaller with increase in motivation," it can be predicted with regard to perceptual tasks measuring cue-utilization and span of attention that performance will be improved under moderate heat but will deteriorate under more severe heat (Figure 7). Under moderate heat, the reduced arousal increases the perceptual bandwidth and more peripherally located stimuli are detected by the observer. When the level of arousal increases with an increase in the environmental warmth, the perceptual field decreases, causing the subject to miss peripheral stimuli (see Bursill 1958).

On the other hand, it is to be expected that signal detection tasks of vigilance type, requiring a restricted span of attention for optimum performance, will show a contrary pattern of change. At ordinary or slightly raised organic temperature, signal detection will decrease, and it will then increase with a further increase in physiological strain up to the point of incapacitation (cf. Wilkinson *et al.* 1964).

Finally, it should be emphasized that subjects of different personality classification will probably behave and perform in dissimilar ways when heat loaded. Tense, introvert subjects, with signs of anxiety and rigidity and characterized by a high habitual level of arousal, probably become more relaxed in de-arousing moderate heat than less compulsive subjects. Therefore their performance will gain on difficult

tasks and on cue-utilization tasks. On the other hand, the performance of extrovert and emotionally labile subjects, with a habitually low or fluctuating level of arousal, will be impaired. A similar reasoning regarding the general relation between level of arousal and personality, but without connection to heat stress research, has been presented by Broadbent (1963 b), Eysenck (1967), and Welford (1965).

Measures of performance

The current problems concomitant with measurement of performance in different working situations are excellently discussed at length by Ryan (1947), Poulton (1965, 1966), and Teichner (1968). Teichner & Olson (1971), with special reference to signal detection, presented a preliminary theory of the effects of task and environmental factors on human performance. Elliott (1960) discussed the possibility in generalizing the results of laboratory studies of vigilance to practical military watch-keeping. Some additional points of special relevance to heat stress research are discussed below.

In some investigations into the effects of moderate heat stress on mental, perceptual, or psycho-motor performance has been studied by using complex tasks or a primary and a secondary task simultaneously administered, requiring the subject to do more than one thing at a time. As mental performance depends on several specific abilities and functions working in different degrees and even in different directions, an integrated measure, derived from a complex performance task, could be hard to interpret and could present inconsistent results. At one stress level, some aspect of performance could be affected, whereas at another stress level, some other aspect could be affected.

Pursuitmeter performance, for instance, requires that the subject's attention is continuously directed on the pursuitmeter display that he can appropriately receive, organize, and interpret the visual stimulation, that he can react motorially, and that he can synchronize his motor act with his visual percept. If the subject's performance is adversely affected, it might be due to

a) a sensory or motorial deterioration, i.e. a peripherally determined effect, or to

b) an impaired synchronization of afferent and efferent impulses via cortical inter-neurons, i.e. a centrally determined effect.

The difficulty of interpreting a complex performance task is illustrated in one of Pepler's studies of pursuit tracking, in which the visibility of the pursuitmeter display was reduced to almost the absolute threshold of perception (Pepler 1960). Did the impaired tracking depend on a further heat-induced reduction of perceptual processes or on influence on other processes? The experimental situation will be even more complicated, and the results will be even harder to interpret if the pursuitmeter is a central task and the subject also has to attend and react to a secondary perceptual task, as in the Bursill lamp test (Bursill 1958). On the other hand, it is highly probable that the subject's performance will be definitely affected at moderate and even at mild stress levels when the task is made more difficult.

In other types of mental work directly focused on centrally determined performance, the subject is obliged to memorize a large number of test items before or at the same time as he must operate with them. This is the case with some types of problem

solving and mental calculation tasks, whereby a performance deterioration might be caused by impaired storage capacity and also by an adverse effect on the subject's cognitive functioning with regard to reasoning or calculation. However, by means of ingenious scoring techniques, some of the shortcomings of complex performance tasks can be overcome (see further below, Psychological methods for measurement of performance).

Research designs

One of the basic methodological questions facing the experimental psychologist is whether he must collect his data by using two or more independent samples or study only one sample in a repeated measures design, obtaining correlated observations. If the first type of design is chosen many treatments and levels of treatment are to be investigated, and the number of subjects required to perform an experiment could be prohibitive. It could also prove very expensive and time consuming to obtain samples of adequate size if the treatments refer to individual characteristics or if the experimenter otherwise wishes to study individual differences, such as skill, intelligence, or personality.

In heat stress research, it is of interest to study partly well-established and practised tasks and partly tasks unfamiliar to the subject and which he has to learn. If the learning process *per se* and the main effects of heat on performance are of interest, only the repeated measures design is applicable. In that case, sequence effects can best be investigated if an order factor is included and the study is designed as a split-plot or mixed experiment.

Because of the advantages of the repeated measures

design, which permit the experimenter to eliminate subject heterogeneity in testing treatment effects, it was decided to carry out the study with one experimental group and to expose the subjects to all climate conditions in random order (see further below, Experimental design and statistical analysis). In order to study psychometric characteristics and learning processes of the performance tasks under neutral environmental conditions, the classical technique of using a control group was adopted. By means of the control group, sequential effects occurring in the experimental group could be suitably interpreted.

P R O C E D U R E A N D M E T H O D S

SUBJECTS

Thirtysix ten-year-old subjects—18 boys, 18 girls—from the fourth grade in the elementary school volunteered to take part in the investigation. They were paid 10 Swedish crowns/h for participating in the experiments.

The records of the school physician and school psychologist were consulted. Children who had shown signs of heart disease, allergy, skin disease, or neurological or psychiatric symptoms of a non-trivial nature were excluded. No auditory diseases had been diagnosed.

The children were randomly assigned to either an experimental group of 24 or a control group of 12 (see further below, Experimental design and statistical analysis). Appendix Table 1 gives the subjects' age, height, weight, and body surface area according to Du Bois (Carpenter 1964). No statistically significant differences were found between the experimental and the control groups.

CLIMATE EXPOSURE

The experiments were carried out in the climate chamber at the Department of Hygiene, University of Lund, Sweden (for description, see Löfstedt 1966). A lithium chloride dew point cell was used in measuring humidity. The water-vapour pressure was kept constant at 15 mm Hg. The air movement was measured with a Kata thermometer and was adjusted by circulation fans to 0.3 m/sec. Chamber temperatures were continuously recorded with eight copper-constantan thermocouples placed 0.2, 0.7, 1.2, and 1.7 m above the floor on both sides of the subject.

Three exposure temperatures were studied: 30°, 36°, and 41°C DB, corresponding to 0, 0.6, and 1.2 units on the P4SR-scale, for subjects dressed in shorts (McArdle *et al.*

1947), and to 24° , 27° , and 29°C basic effective temperature (Bedford 1946). For normally-clothed subjects (1 clo), the same degree of physiological strain would be caused by about 23° , 30° , and 36°C (Löfstedt & Eriksson 1970). The climates were chosen so that they should partly correspond to relevant indoor dry bulb temperatures in Swedish schools, and partly coincide with those effective temperature values that, according to the review, are to be considered crucial for performance.

The chamber climate was automatically and continuously regulated to achieve the designed conditions. Acoustic and lighting conditions were the same throughout the experiments (75 dB-C, 65 dB-A, respectively, about 100 lux).

Every exposure lasted three hours, beginning at 8 a.m., noon, or 4 p.m. The subjects were assigned in equal numbers to each of the three hours (see further below, Experimental design and statistical analysis). Each subject participated in three exposures, with intervals of two or three weeks between the exposures, and at the same hour each time in order to eliminate any possible diurnal effects. In all, 108 exposures were made. Before the exposures, the subjects were tested for certain psychological characteristics (see further below, Psychological methods for measurement of ability, personality and other individual characteristics). In connection with this testing, the subjects were shown the climate chamber and were thoroughly informed about the experimental procedure; but at no time was information given about climate conditions, order of presentation, or what results they had achieved on any of the performance tasks.

The equipment for the physiological recordings was attached to the subject before each exposure began. The climate chamber contained a table, and the subject sat in front of it on a deck chair with seat and back

of plaited ribbons. As they wore only shorts, most of the body surface was exposed to the air. During the exposures, the subject was allowed to drink water ad lib. The subject could at any time communicate with the experimenter by means of a microphone and a loudspeaker. Through two one-way screen windows, the subject could be observed without his knowledge. When not being tested for mental and perceptual performance, the subject could draw, write, or read at will.

The investigation was performed during the spring, from mid-April to the beginning of June.

PHYSIOLOGICAL METHODS

The following physiological data were recorded:

a) rectal temperature, continuously recorded by a platinum resistance element and potentiometer recorder (sensitivity $\pm 0.05^{\circ}\text{C}$);

b) skin temperature, continuously recorded on a potentiometer recorder as an unweighted mean of thermocouples attached to the leg just above the ankle, to the thigh, to the back, and to the upper arm (sensitivity $\pm 0.15^{\circ}\text{C}$);

c) mean body temperature, calculated according to Burton's formula: $0.65 \times \text{rectal temperature} + 0.35 \times \text{mean skin temperature} = \text{mean body temperature}$ (Burton & Edholm 1955);

d) pulse rate, continuously recorded for about two minutes each quarter hour by means of ECG-electrodes fixed to the chest by a belt and placed over the apex of the heart and to the right of the sternum;

e) sweating, measured as weight loss with correction for water intake (sensitivity $\pm 25 \text{ g}$). (For further descriptions and technical details, see Löfstedt 1966.)

PSYCHOLOGICAL METHODS FOR MEASUREMENT OF PERFORMANCE

In order to simplify the interpretation of the influence of heat stress on mental and perceptual work, performance was measured in the present experiment by a number of comparatively simple tasks, each one intended to focus on one specific psychological ability or function. The choice of tasks was determined with regard to the tasks' use in and relevance for school work. The tasks were further selected to be reliably measurable and practicable within the given limits of time, available apparatus, and personnel. A further requirement was that they should be performed over a sufficient length of time for the strain not to be overcome by an occasional compensatory strenuous effort (arbitrarily 10 min). Finally, the tasks should be sensitive to changes in arousal and motivation. The following aspects of performance were chosen: paired-associates learning and memory (storage and recall functioning), mental calculation (arithmetical coding), gestalt perception (predominantly perceptual and storage processes), attention and cue-utilization (auditory and visual search, respectively).

The selection and design of the tasks were based on a pilot study of 20 children, none of whom took part in the main experiment. The goal was to obtain a measurable performance from the less competent children and to prevent the more competent ones from achieving maximum score. Table 12 shows the order in which the tasks described below were presented during the heat exposure.

The learning tasks consisted of 12 pictures, each represented by a nonsense syllable of three letters, according to Glaze (Appendix Figure 1). As far as possible, the order of the syllables was constructed in accordance with rules proposed by Luh and later

Task	Test time	Cum. time
Learning 1	"unlimited"	0 min
CFF 1	5 min	30 min
Multiplication	15 min	40 min
Rest	about 5 min	55 min
Weighing	about 5 min	60 min
Partington 1	45 sec	65 min
Addition	15 min	70 min
Retention 1:1	2 min	85 min
Partington 2	75 sec	90 min
CFF 2	5 min	95 min
Rest	about 10 min	105 min
Auditory Startle Response	about 5 min	115 min
Weighing	about 5 min	120 min
Learning 2	"unlimited"	125 min
APT	"unlimited"	155 min
Retention 1:2	2 min	165 min
Retention 2	2 min	170 min
Rest	about 5 min	175 min
		180 min

Table 12. Test procedure.

modified by Melton (see Hilgard 1951). The pictures were presented in succession on a screen in the chamber by an automatic projector with a constant exposure of 7.5 sec/picture. The same 12 pictures were then exposed without any letters for 10 seconds each. The subject was to say the syllables accompanying the pictures, in accordance with the paired-associates learning method. Each correctly identified picture was removed from the series in order to avoid overlearning. The procedure was repeated until every picture had been correctly named. The performance was measured in terms of the number of exposures required. Six equally designed series were used.

Memory was examined by again presenting the pictures from the learning task after an interval of time. The retention was reported as the number of correctly remembered letters in the right place in the syllable.

As Table 12 shows, two versions of the learning task were administered at each exposure. In order to test for the existence of progressively increasing heat effects on learning performance, one version was given at the beginning of the exposure, and the other version after two hours' exposure. For the same reason, a first measurement of retention was made after 85 minutes and a second measurement after the lapse of a further 80 minutes of heat exposure.

Two numerical tasks were used: Addition and Multiplication. Each consisted of 214 items. The first, addition of two two-digit numbers; the second, multiplication of two digits by one in accordance with DBA (Differentiell Begåvnings Analys; Härnqvist). The total number of items calculated during 15 minutes and the error percentage were scored. These represented speed and accuracy, respectively. Three parallel forms of each task were constructed.

The Gestalt Perception task—APT (Animated-design Perception Technique; Johnson & Weikert 1964, Johnson, Nilsson & Weikert 1968)—consisted of nine geometric designs (Appendix Figure 2). Each item in turn was projected onto the screen in the chamber in the form of a spot of light moving evenly along a predetermined path (the design). The subject had to reconstruct the design immediately after its presentation. Two separate methods of scoring were used: raw score (0 or 1) for principal parts and bonus score for minor details. Two films with identical designs, but presented in different orders, were used.

The Auditory Startle Response was examined with a 1000 Hz sine wave. First, with no previous warning, three signals were presented in rapid succession 45 dB below the background noise level in the chamber (75 dB-C, 65 dB-A). The sound pressure level was then raised in steps of 5 dB until a startle response—i.e. turning the head towards the source of noise, sudden movement, interruption of on-going activity, questions—was observed. This reaction was sometimes a genuine startle response but was more often observed in the form of scattered attention and of distraction reactions.

The subjects had not been informed about the presentation of the acoustic signals. If they asked what the sound was or its source, they were told that it was caused by an occasional fault in the auditory communication system which would be repaired.

The Partington's Pathways-Test (Partington & Leiter 1949, Ammons 1955) in its two original parts was used.

In both parts, 25 circles are randomly scattered over the test sheet. The subject has to draw a line from the labelled "start" position (circle 1) through the circles in their proper sequence. In Partington 1,

the sequence is given only by numbers as 1, 2, 3, ... 23, 24, 25; in Partington 2, by alternate numbers and letters as 1, A, 2, B, ... K, 12, L, 13 (Appendix Figure 3). The correctly drawn line never crosses its own path.

The performance measure was the number of items correctly connected in 45 seconds for the easy part one (numbers) and in 75 seconds for the difficult part two (numbers-letters). Three parallel versions of each part were constructed by inverting the original pathway and taking its mirror image. According to Eysenck & Willett (1962), Partington's Pathways-Test can be considered a measure of cue-utilization.

The critical flicker frequency task (CFF) was designed according to the principle of the Bekesy audiometer or the psychophysical "up-and-down" method.

A square wave generator with variable frequency, feeding a specially constructed neon bulb, can be operated by remote control. At fusion, the subject has to decrease the frequency until he perceives flicker, then increase it to fusion, and so on. No fixed frequency can be maintained. The light intensity of the neon bulb is fixed. The CFF is calculated as the mean of all extreme fusion and flicker frequencies during five minutes.

For every subject, the task started alternately from fusion and flicker. The object is intended to measure attention and ability to take decisions, rather than in the common way to be considered a measure of central nervous over-all activity. The task differs from the others in that it contains sensory as well as motor processes and therefore must be considered complex.

The subject was accompanied in the closed chamber by

the experimenter during the exposures to the following tasks: Learning 1 and 2, Retention 1:1, 1:2, and 2, Partington 1 and 2, and CFF 1 and 2 (Table 12). The rest of the tasks were introduced by the experimenter in the chamber, the subject then being left alone.

With respect to the learning and memory tasks and the two numerical tasks, the subjects were expected to obtain an optimum performance in the reference condition. Under heat load, the performance would probably be impaired—at 0.6 P4SR because of under-arousal and at 1.2 P4SR because of over-arousal. According to the outlined arousal hypothesis, it was predicted that an inverted U-shaped heat stress performance relation would appear on the perceptual tasks measuring attention and cue-utilization, as the perceptual field would be largest at somewhat reduced arousal in the middle climate. At 0.6 P4SR, the increase in the perceptual bandwidth would result in a lowering of the auditory startle response threshold and a gain in the number of correctly connected items on the Partington's Pathways Test. The inverted U-shaped pattern, predicted by the arousal hypothesis, would probably be more marked on Partington 2 than on Partington 1, because Partington 2 must be considered as a more difficult test of cue-utilization than Partington 1 (see also above, Problem analysis).

After each exposure, the subjects were interviewed with respect to thermal sensation, their experience of the experimental situation, and the performance tasks.

PSYCHOLOGICAL METHODS FOR MEASUREMENT OF ABILITY, PERSONALITY, AND OTHER INDIVIDUAL CHARACTERISTICS

Intelligence data, measured by WIT II (Westrin's Intelligence Test II—for syllabus 4 and 5; Westrin

1969), were obtained from the school psychologist.

WIT II is a conventional group test of factor type containing five subtests: three verbal: Sentence completion, Arithmetic, Object assembly; two non-verbal: Picture completion and Figure identification. Subtest scores are transformed according to the stanine norm ($m=5$; $s=2$), whereby the subjects can be grouped in nine categories containing 4, 7, 12, 17, 20, 17, 12, 7, and 4%, respectively, in each category. The stanine scores of the subtests can then be added together and the resulting sum finally transformed to a total stanine score. This score is used as a measure of general intelligence. Both subtest and total stanine scores were used in the Q-factor analyses (see below, Experimental design and statistical analysis).

Before exposure, the subjects were tested for numerical ability by DBA 8A (addition) and DBA 9A (multiplication) according to Härnqvist, for cue-utilization by the original Partington's Pathways-Test, and for cognitive and personality characteristics by the serial Color-Word-Test (CWT; Smith & Nyman 1964, 1972).

CWT is a modified form of the Stroop test (Stroop 1935) and consists of 100 colour-words: red, blue, green, and yellow, randomly arranged and printed in incongruent hues, i.e. the colour-word red is printed in blue, green, or yellow, but never in red. The subject is instructed to name the printing-hue and ignore the printed colour-word. The reading time is registered after every block of 20 words, and five time-scores are thus obtained for each of five identical reading pages (subtests). The subject's way of handling the discrepancy between the colour-words and the printing-hues is reflected in the serial pattern of his reading speed and can be investigated by regression analysis. The regression of the time-scores on the five blocks of 20 words within each subtest (R) and the residual variance (V) are calculated.

The subjects are categorized in three groups with respect to their adaptive patterns. Cumulative subjects (C_k) are characterized by steadily increasing

reading difficulties and time scores due to their inability to solve the cognitive conflict and to ignore habitual controls and irrelevant expectations. Thus they cannot refrain from reading the printed words instead of the printing hue, and this difficulty is more pronounced the more they are exposed to the discrepancy stress. The R-values of one of the first two subtests and of at least three of the five subtests exceed the medians. Subjects with correspondingly high V-values are labelled dissociatives (D_k). Their distinguishing features are fluctuating time scores and unstable cognitive control in connection with inattention. The dissociatives can occasionally cope with the interference conflict, but they then suddenly lose control over their cognitive functioning, obtaining high time scores which reflect great reading difficulties. Their time scores fluctuate, indicating recurrent difficulty in dealing with the interference conflict. Stabilizers (S_k) are characterized by an evenly-maintained reading speed and unvaried time scores, and thus they cannot be classified as either C_k or D_k . Their adaptive pattern reflects an ability to cope successfully with the interference and suppress irrelevant anticipations.

The stabilizers were used as a reference group for performance comparisons with the cumulatives and the dissociatives, whereas comparisons were never made between cumulatives and dissociatives, as a subject could be included in both categories (CD). In connection with the performed Q-factor analyses (see below, Experimental design and statistical analysis), the ordinary way of classifying subjects with respect to secondary and initial type was also used. Furthermore, R- and V-index were used, based on cumulated R and V values, respectively. All classifications were based on own norms in accordance with prevalent usage in experimental research on normal instead of clinical groups.

The serial Color Word Test has been developed on adult clinical groups; comparatively little research has been done on samples of young subjects. In previous investigations on psychiatric and other groups (Smith & Nyman 1964, 1972), the cumulative pattern has been found to indicate compulsion and has frequently been found among patients displaying manifest anxiety in connection with phobia or obsession, but without asthenic, inhibitory, depressive, or hysteroid traits. This pattern has also been found to be characteristic of women with many *post partum* symptoms (Nilsson & Almgren 1970). A study by Trygg (1972) on mental multiplication in environmental warmth showed that cumulative subjects were most affected by the heat when the task-load was high.

Infantile and hysteroid patients with conversion, but not compulsive-obsessive, reactions and without manifest anxiety are associated with the dissociative

pattern. *Bliding et al.* (1966), in a study of the effects of heat load on mental multiplication with moderate task load, reported, that subjects with a rectal temperature above the equilibrium limit of 38°C were most affected, provided they were also classed as dissociative. When CWT-tested under neutral conditions, the dissociatives displayed increased pulse rate during the whole testing without any signs of physiological adaptation. The dissociative pattern has been reported to occur more frequently among accident-loaded than among accident free young car drivers (Andersson, Nilsson & Henriksson 1970). According to Nilsson & Tibbling (1972), dissociative subjects have a greater cigarette consumption than the other CWT categories.

The stabilized pattern is most frequent among psychically normal and well-adjusted persons. No statistically significant differences between cumulative and dissociative subjects, on one hand, and stabilized subjects, on the other, appeared in a study by Arvidsson *et al.* (1965) on the experience of noise and its annoyance. This suggests that the test is insensible to such cognitive processes as are linked to assessment of sensation.

Before exposure, the subjects were also interviewed with respect to previous thermal experience and acclimatization. The questionnaire asked about clothing indoors and outdoors, perceived temperatures at home and in school, and preference for and frequency of sun-bathing and sauna bathing.

EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

The investigation was designed as a factorial experiment with temperature and order of the climates balanced in a twice replicated design— 3^2 randomized block partially confounded factorial design (RBPF design, Kirk 1968, p. 320)—as shown in Table 13. The same type of design was used balancing task versions and their order for the control group. The subjects in the two groups were randomly assigned to the six possible permutations of climate sequence, each sequence

containing four subjects in the experimental group and two in the control group.

Replication 1	Climate sequence 1	0 ₁	1.2 ₂	0.6 ₃
	Climate sequence 2	0.6 ₁	0 ₂	1.2 ₃
	Climate sequence 3	0.6 ₂	1.2 ₁	0 ₃
Replication 2	Climate sequence 4	0 ₁	0.6 ₂	1.2 ₃
	Climate sequence 5	0 ₂	1.2 ₁	0.6 ₃
	Climate sequence 6	0.6 ₁	1.2 ₂	0 ₃

Table 13. Partially confounded factorial design for the experimental group. Subscripts show order of presentation of the climate conditions expressed in P4 SR units.

Each sequence represented one of six possible sequences of administering the climates; therefore it was decided not to analyse the data in accordance with the statistical model for a RBPF - 3^2 design, which precludes the use of treatments representing successive periods of time. Instead, the data were analysed in accordance with a mixed linear model of a factorial design with sequence and temperature (repeated variable) confounded and treated as fixed effects. As shown in Appendix Table 2, this model makes it possible to evaluate not only main effects of climate sequence and temperature, but also simple main effects, and through these effects to obtain information on learning as a third variable (Kirk 1968, p. 245).

Homogeneity of variance was tested by Cochran's C-test. Significant over-all F-ratios were followed up by comparisons between means for main and simple main effects with the aid of Tukey's HSD test (Honestly Significant Difference test) for pairwise comparisons and Scheffé's S-method for complex comparisons. If

a significant F-ratio and non-significant HSD and S tests were obtained, Fisher's LSD-test (Least Significant Difference test) was used. For testing simple main effects of sequence, the between-subject variance component, used for testing main effects of sequence, and the within-subject component, used for testing main and simple main effects of temperature, were pooled to form the error term. Significant temperature effects were also investigated by trend analysis, whereby linear and quadratic mean squares were tested against their corresponding parts of the within-subject variance component (see Appendix Table 2). Missing scores were estimated by a procedure described by Yates. Tasks with four or more subjects with missing scores—a number corresponding to a complete block—were analysed by conventional t-test for related observations, i.e. individual differences, whereby the subjects with missing scores were discarded.

Scores which were not normally distributed and data obtained from stratified groups (strain, ability, skill, and personality groups) were analysed by non-parametric statistics: Friedman's two-way analysis by ranks, Cochran's Q-test, and Wilcoxon's matched-pairs signed-ranks test, all testing related samples; also Kruskal & Wallis' one-way analysis by ranks, and Mann & Whitney's U-test, which test independent observations (Siegel 1956). Unless otherwise stated, hypotheses were always tested two-tailed. Level of significance is presented symbolically as follows: *** denotes 0.001, ** denotes 0.01, * denotes 0.05, and o denotes 0.1 significance.

To summarize: The adopted research paradigm presented in Figure 6 a, the experimental design presented in Table 13, and the statistical analyses described above and in Appendix Table 2 make it possible to study the effects of the heat stress on each of

different types of mental and perceptual performance tasks (Figure 6 a Question 1). Significant over-all effects can be thoroughly followed up by testing means for main and simple main effects and by tests for trend.

With respect to heat-induced performance changes, the significance of each one of different individual characteristics, such as physiological and psychological strain, ability, and personality, can be studied by comparisons of subjects with high and low rectal temperature (Figure 6 a Question 2), of subjects reporting the climate "just right, too warm, or hot" (Figure 6 a Question 3), of competent and less competent subjects (Figure 6 a Questions 4, 5), and by comparing subjects that show stable cognitive control with rigid subjects and with subjects that display unstable control (Figure 6 a Question 6).

Although the planned statistical analysis thus was rather comprehensive, indicating the importance of several variables separately (Figure 6 a), the question of who was heat affected with respect to mental performance was unanswered (Figure 6 b). The questions posed in Figure 6 a—and answered in Tables 16-23 and Table 25—are focused on whether the effects of heat stress on performance are influenced by rectal temperature, pulse rate, sweat rate, psychological strain, general intelligence, skill, and/or personality *per se*. Thus the analysis of variance technique does not indicate whether the adversely affected subject was depicted by one or several individual characteristics that distinguish him from the unaffected subject. Much less did the analysis indicate the pattern of these characteristics within the individual, or whether there existed a number of subgroups of heat affected and/or unaffected subjects, with each subgroup depicted by a certain pattern of individual characteristics.

In order to give a comprehensive and global description of all significant physiological and psychological characteristics of subjects with different degrees of heat-induced performance changes, the analyses of variance were supplemented by analyses of distribution and factorial grouping of these characteristics within the experimental group. The statistical tool used for this work was Q-factor analysis, according to Holley (1974). As the Q-methodology, similar to factor analysis in general, is less well suited for direct test of hypothesis, the technique was used only for exploratory purposes (cf. Harman 1967, p. 5-6). Moreover, it was intended to test the applicability of Q-methodology to experimental data, as most Q-factor analytical studies have been performed on clinical data.

As illustrated in Figure 6, there is a fundamental difference between the two approaches of analysis. Questions 1-6, presented in Figure 6 a, are unambiguously and unequivocally stated before any experiment is performed and without any information about the reactions of the subjects. They are testifiable research hypotheses and can only be answered "yes" or "no". The six questions and the answers to them might explain the effects of heat stress on performance. Contrary to this, Questions 7-9, presented in Figure 6 b, do not explain anything. They are asked after the experimental work is carried out and ended, when the general effects of heat stress on performance are known; i.e. when Question 1 in Figure 6 a is answered, Questions 7-9 are presented. They are so formulated that they are only explorative and descriptive. In contrast to Questions 1-6, Questions 7-9 cannot be completely answered by "yes" or "no". They are intended to describe in which respects more and less performance affected subjects differ. Whereas Questions 1-6 are focused on whether the effects of heat on performance are related to

specific variables *per se*, Questions 7-9 are focused on what interrelations between these variables characterize, and distinguish adversely and not adversely affected subjects. The statistical significance of the answers to Questions 7-9 cannot be unbiasedly estimated unless the Q-factor analysis is replicated and the results are cross-validated in a new study.

Because the reader might not be familiar with the adopted version of Q-factor analysis, the main characteristics of the technique will be described.

The first step in the multi-dimensional analysis was to depict the subjects with regard to the individual characteristics under study. Each subject was therefore described and identified at each hour of exposure under heat load by between 219 and 226 items, covering all the recorded physiological measures and all psychological measures of intelligence, pre-exposure test performance, skill, personality, and other individual characteristics and also the subjective reports of the post-exposure interview. The number of items depended on the performance task, i.e. one specific item list was worked out for each performance task. Thus a separate Q-factor analysis was made with respect to each performance task in each of the two stress climates.

In order not to lose too much information and still meet the methodological pre-requisites of Q-factor analysis, most of the items were obtained by dichotomizing each variable on different levels; arbitrarily, the dichotomization was made with respect to each one of the quartile points. The rectal temperature or the intelligence of a subject could, for instance, be described as being above or below the first quartile point (item a), or the median (item b), or the third (item c). This was considered the best way of obtaining an adequate differentiation, as the items used for Q-factor analysis must be dichotomous, but they do not have to be independent (Jonsson 1973, Holley 1974).

The next step in the analysis was to investigate to what extent the items could discriminate between the most and the least adversely affected subjects on each task. Performance deterioration was defined with regard to the median change of performance under heat load with the performance score in the neutral climate as reference. For those tasks where a large number of the subjects above the median were adversely affected, the discriminatory power of the items was also calculated, with reference to their possibility of

differentiating the truly affected subjects from the unaffected subjects.

The discriminatory power of each item was calculated as a specific statistical index, D-index, presented by Holley & Risberg (1972). The D-index is a measure of the difference between two independent proportions; in this case, the difference between the proportion of subjects having an item characteristic and scoring above the performance change median (or alternatively keeping their performance unchanged or improving it), on one hand, and the proportion having the characteristic but scoring below the median (or alternatively deteriorating), on the other hand (Appendix Table 3).

The observed frequency distribution of the D-index was compared with the theoretical frequency distribution, which in turn was obtained by means of probability calculus, and goodness of fit was analysed by χ^2 -testing. The D-index analysis was accordingly carried out in order to discover whether the affected and unaffected subjects differed with respect to all studied individual characteristics.

The final step in the multi-dimensional analysis was to calculate the correlation or degree of agreement between the subjects in the experimental group and to factor analyse the correlation matrix. Note: in Q-factor analysis, subjects are correlated; in the common R-factor analysis, items or tests are correlated.

The correlation was calculated by means of the G-index of agreement, given by the formula $G = 2p - 1$ (Holley & Guilford 1964, Holley & Sjöberg 1968). The G-index is a non-parametric statistic based on the proportion of dichotomous items (p_c) that are answered in the same way by two subjects (p_c) (Appendix Table 4). By changing the item polarity and scoring each item twice, i.e. each item will be scored both + and -, the ipsative score (person centred) requirement of Q-factor analysis is met (Holley 1964).

The Q-factor analysis of the G-index matrix was made in accordance with the principal component method. Kaiser's criterion (Harman 1967, p. 198) was used for extraction of factors, implying that the eigen value of the extracted factors was equal to or greater than 1.00. Rotations of factors thus extracted were carried out by means of the varimax procedure. As the factors are constituted by subjects and not by tasks, as is the case in R-factor analysis, the factors must be described with reference to the items characterizing the subjects in order to obtain psychological meaning. The items identifying the factors were selected with a weighted discriminatory index—D(w)-index—suggested by Risberg (1972). The D(w)-index is weighted with regard to the square of the factor loading of the subjects.

Finally a few facts must be emphasized.

First, in all types of factor analyses, the final factor solution depends on the arbitrarily chosen criterion for extraction of factors. It could be concluded that there are as many factor solutions as there are extraction criteria.

Secondly, in opposition to R-factor analysis, with the interest focused on the correlations between some tests (correlations computed on the basis of randomly sampled subjects), the interest in Q-factor analysis is centred round similarities among selected subjects; similarities studied with regard to the subject's responses to a number of more or less arbitrarily chosen tasks and arbitrarily dichotomised items.

Thirdly, in experimental research, the definition of a performance change is arbitrary and so are also the categories "adversely affected" and "unaffected". In this study, a performance deterioration is defined with regard to the median change of performance under heat load, with the performance score in the neutral climate as reference. However, a performance deterioration could equally well have been defined with the aid of some other arbitrary criterion. The facts discussed under the second and third point mean that the factor solution is a function of the item list and of the definition of an experimental effect. Consequently the user of Q-factor analysis can influence the factor solution through his choice of items and distribution of subjects.

Fourthly, the discriminatory power of the items characterizing the extracted factors are arbitrarily determined; therefore a factor might be described by only a few or a large number of item characteristics, depending on the chosen cut-off value of the discriminatory index.

In view of these facts, it was decided to use the Q-factor analysis technique as an exploratory and

purely descriptive method. As a method for testing hypotheses, it has doubtful validity. Only factor solutions that appeared to give a psychologically meaningful description of adversely affected and of unaffected subjects are presented (cf. Harman 1967, p. 198, distinguishing between "practical" and statistical significance). The only methodologically satisfying way of confirming the results of the Q-factor analyses would be to crossvalidate the discriminatory power of the items and the obtained factor solutions on a new population sample. This will be the aim of future research.

RESULTS AND DISCUSSION

PHYSIOLOGICAL DATA

Reliability and validity of physiological measures

Table 14 shows the physiological data recorded during the last hour of exposure for the control group at the three exposures in the neutral climate.

Trial	1	2	3	r_{12}	r_{13}	r_{23}
Rect.temp., °C	37.27 ⁺ .30	37.34 ⁺ .21	37.34 ⁺ .24	.79 ^{***}	.55 [*]	.75 ^{***}
Skin temp., °C	34.33 ⁺ .59	34.58 ⁺ .31	34.37 ⁺ .27	.33	.48	.57 [*]
Mean body temp., °C	36.24 ⁺ .36	36.39 ⁺ .17	36.30 ⁺ .16	.59 [*]	.51 [*]	.67 ^{***}
Pulse rate, beat/min	94 ⁺ 14	93 ⁺ 11	93 ⁺ 9	.83 ^{***}	.89 ^{***}	.89 ^{***}
Gross sweat rate, g/h	37 ⁺ 21	25 ⁺ 43	41 ⁺ 12	.11	-.48	.01
Sweat rate, g/m ² /3h	114 ⁺ 28	113 ⁺ 22	107 ⁺ 32	.54 [*]	.49	.62 [*]

Table 14. Physiological data for the control group at the three trials in the neutral climate, O P4SR—except for sweat rate g/m²/3h. † recorded during the last hour of exposure (120-180 min)—mean ± standard deviation. The table also shows the product-moment correlation for each of the physiological measures (* denotes 0.05, ** denotes 0.01 and *** denotes 0.001 statistical significance).

The mean values for the recorded physiological variables and the product-moment correlation between values at different trials indicated that rectal temperature and pulse rate varied little between the three trials in the neutral climate, O P4SR or 24°C ET. Thus they were the most consistent measures of physiological function at different trials under identical exposure conditions. Therefore, the physiological resting level with respect to these two measures could be rather accurately estimated for each individual. For the heat exposed subject in the experimental group, it would thus be adequate to describe the physiological strain under heat load by means of either the absolute measure of rectal temperature and pulse rate, or the deviation measure in these respects, i.e. the deviation of rectal

temperature and pulse rate under heat load from the resting level values recorded in the neutral climate of O P4SR.

On the other hand, the gross sweat rate, g/h, was unpredictable at one trial from knowledge of its value at another trial, as indicated by varying means and correlation coefficients. The correlation coefficients of gross sweat rate indicated that a subject could be strongly perspiring at one trial under neutral conditions, whereas at a subsequent trial in O P4SR his gross sweat rate was relatively low. This means that the deviation measure of gross sweat rate would be an inadequate measure of the physiological strain under heat load, because it was not possible to reliably estimate the resting level of gross sweat rate.

In contrast to gross sweat rate, g/h, the sweat rate, g/m^2 (body area)/3h, was more consistent between trials, but the inter-trial correlation was lower than for rectal temperature and pulse rate and differed, in one case not statistically significant, from zero (see further below, The relation between exposure duration and degree of physiological strain).

Physiological reactions in heat

Table 15 presents physiological data for the control and the experimental groups recorded during the last hour of exposure.

There was no difference between the control and the experimental group in the reference climate. Apart from pulse rate, which was above the ordinary resting level, as was noted for the control group at each of the three thermally neutral exposures (see Table 14), both groups were characterized by ordinary

Subjects	Control		Experimental			r_{intra}	r_{inter}
	24°C	O P4SR	24°C	O P4SR	29°C		
Effective temp.							
Heat stress index							
Rect. temp., °C	37.32 ⁺ .25		37.31 ⁺ .14	37.62 ⁺ .24	37.96 ⁺ .22	.88***	.47**
Skin temp., °C	34.43 ⁺ .42		34.31 ⁺ .42	35.95 ⁺ .35	37.15 ⁺ .33		
Mean body temp., °C	36.31 ⁺ .26		36.27 ⁺ .15	37.02 ⁺ .26	37.68 ⁺ .23		
Pulse rate, beat/min	93 ⁺ .11		93 ⁺ .11	105 ⁺ .12	115 ⁺ .16	.93***	.74***
Gross sweat rate, g/h	34 ⁺ .28		40 ⁺ .31	120 ⁺ .30	217 ⁺ .61	.14	.18
Sweat rate, g/m ² /3h	110 ⁺ .26		111 ⁺ .32	313 ⁺ .66	545 ⁺ .47		.46**

Table 15. Physiological data—except for sweat rate g/m²/3h, recorded during the last hour of exposure (120-180 min)—mean± standard deviation. No differences between control and experimental group are statistically significant; all differences within the experimental group between the climate conditions are statistically significant beyond the 0.001-level. The table also shows the mean value of the product-moment correlation calculated partly between each of the physiological measures—rectal temperature, pulse rate, and gross sweat rate, g/h—at the first hour, and the same measure at the second and third hour (r_{intra}), partly between each of the physiological measures at 0.6 and the same measure at 1.2 P4SR (r_{inter}). ** denotes 0.01, *** denotes 0.001 statistical significance).

physiological resting values.

Under heat load, all strain measures were affected in the experimental group. The effects were statistically significant both in the middle climate and at 1.2 P4SR. Furthermore, the differences in the values at 1.2 P4SR and the lower values at 0.6 P4SR were significant.

The average increase in physiological strain for all the strain measures was proportional to the rise in thermal stress. This indicates that the P4SR is a valid measure of heat stress.

Figure 8 shows mean values for rectal temperature, pulse rate, and sweat rate for each of the three hours of exposure at 0, 0.6, and 1.2 P4SR.

Irrespective of the environmental temperature, the rectal temperature tended to increase from the first hour of exposure to the second, and to increase further to the third. However, two-tailed t-tests showed that the increase from the first to the second hour of exposure was greater during heat load at 0.6 or 1.2 P4SR— 0.06°C and 0.07°C , respectively—than it was in the neutral reference climate— 0.1°C ($2 p < 0.05$).

The increasing pattern was also noted for the gross sweat rate, g/h, at 1.2 P4SR, but the increase from the second to the third hour was slight and not statistically significant.

The opposite pattern with decreasing values over time was found for the pulse rate, except in the warmest climate—1.2 P4SR—where the pulse rate remained constant throughout the exposure. During the last hour, the decrease of pulse rate at 0 and 0.6 P4SR was different from the small increase at 1.2 P4SR ($2 p < 0.05$).

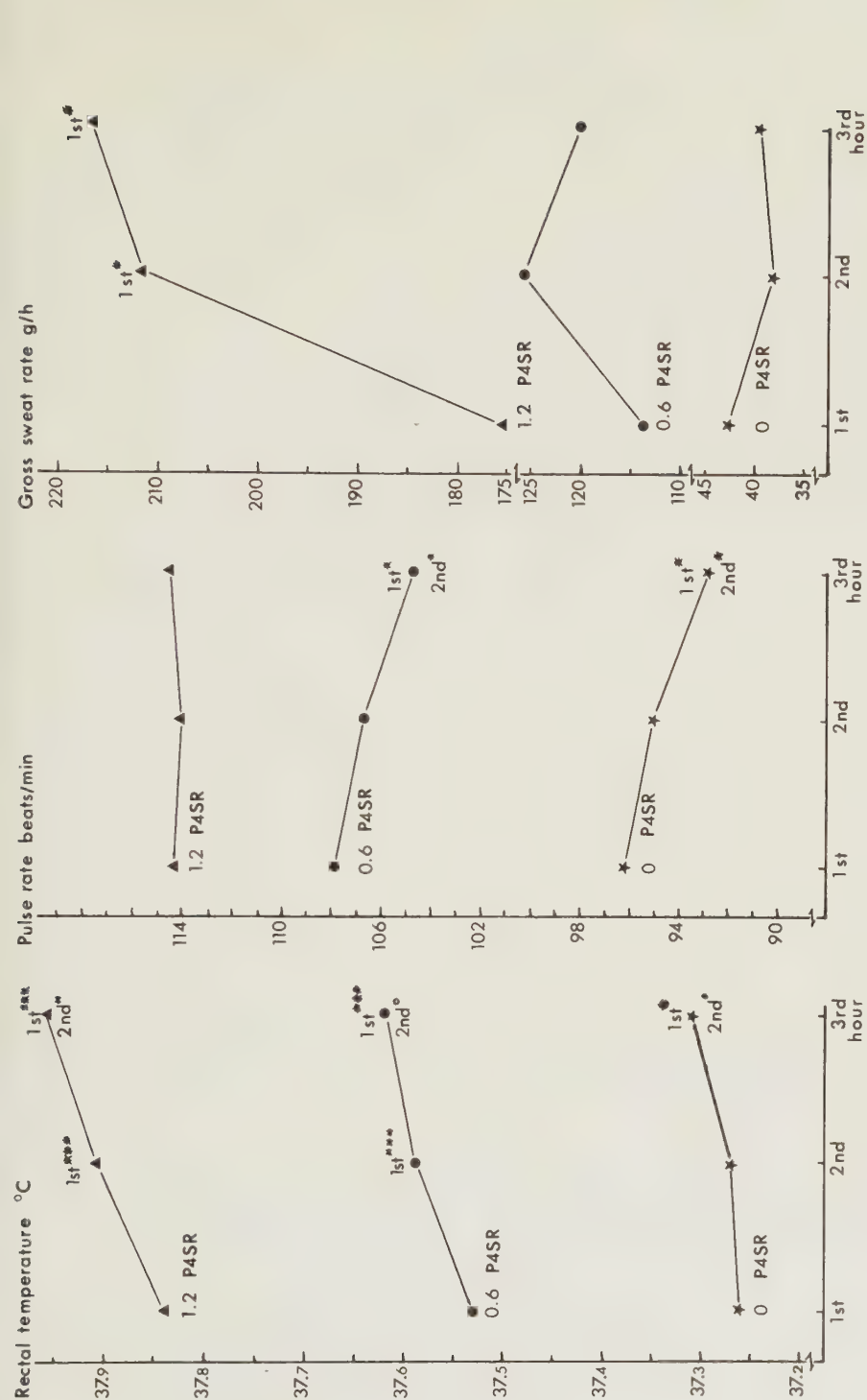


Figure 8. Physiological data—rectal temperature (a), pulse rate (b), and gross sweat rate (c)—for the experimental group during the first, second, and third hour of exposure at 0 (★), 0.6 (●), and 1.2 P4SR (▲) (○ denotes 0.1; ★ denotes 0.05; ** denotes 0.01; *** denotes 0.001 statistical significance).

Intra-exposure consistency of physiological reactions

The time serial analyses of the means of rectal temperature, gross sweat rate, and pulse rate reflect the average group trend during the heat exposures. However, they do not reveal whether it was the same subjects who were physiologically heat affected throughout the exposure, or whether those subjects that were initially heat affected were able, after the first hour of exposure, to counteract the initial upset of the heat balance by an efficient thermoregulation. Therefore the product-moment correlation was calculated for each of the physiological variables between the value recorded during the first hour and the value recorded at the second or the third hour. Table 15 (r_{intra}) shows the mean values of these coefficients in the experimental group.

Rectal temperature and pulse rate in the second and third hour could be reliably predicted from the values in the first hour in all conditions; high correlation coefficients were obtained, being statistically significant at the 0.001 level.

However, for gross sweat rate, g/h, no significant correlation was found. Thus it was impossible to predict the gross sweat rate during the second and third hour from knowledge of its value during the first or second hour of exposure, as was the case for rectal temperature and pulse rate.

Inter-exposure consistency of physiological reactions

Another question was whether the intra-exposure consistency of rectal temperature and pulse rate has an equivalent inter-exposure consistency, i.e. do subjects with high strain values at 0.6 P4SR also

obtain high values at 1.2 P4SR?

A graphical analysis (not shown) indicated that there was an approximately linear positive association for each of the physiological variables between the values recorded at 0.6 and at 1.2 P4SR. Table 15 (r_{inter}) shows the mean values of the product-moment correlation coefficients which express the strength of the relation.

Absolute values of rectal temperature, pulse rate, and sweat rate, $\text{g/m}^2/3\text{h}$, could be reliably predicted at 1.2 P4SR from the values at 0.6 P4SR. A corresponding analysis of deviation values, i.e. the difference between the subject's resting value in the neutral climate and his value when heat exposed at 0.6 and 1.2 P4SR, respectively, indicated that physiologically affected subjects who strongly deviated in the middle climate also deviated markedly when exposed to the warmest condition.

However, it was impossible to predict rectal temperature and gross sweat rate, g/h , under thermal load from knowledge of the resting values in the thermally neutral climate. On the other hand, this could be done for pulse rate ($r = .58^{**}$) and for sweat rate— $\text{g/m}^2/3\text{h}$ ($r = .46^{**}$).

The interrelations between different physiological reactions

The interrelations between the different physiological variables—rectal temperature, pulse rate, and sweat rate—were studied by analysis of regression and correlation (not shown).

Between rectal temperature and pulse rate, a significant linear, positive correlation was found for all

conditions. This relation was more marked when the analyses were based on deviation values (mean $r = .61$) than when they were performed on absolute values (mean $r = .45$). An increase in rectal temperature was thus accompanied by an increase in pulse rate. This relation, being most marked in the warmest climate, is concordant with post-work data by Edholm *et al.* (1962) and resting data by Löfstedt (1966), who reported the pulse rate increase to be linearly correlated with the mean body temperature according to the Burton formula.

No significant linear correlation existed between the rectal temperature or the pulse rate, on one hand, and the sweating measures, on the other. As far as could be seen from the graphical analysis, the sweating measures were not curvilinearly related to rectal temperature and pulse rate, as reported by Löfstedt (1966), who used multiple linear and curvilinear regression analysis to study the relation.

The absence of any relation between sweating and rectal temperature in this study might be associated with the method of analysis; curvilinear relations can be difficult to detect by ocular inspection. However, it is more probable that the nonexistent relation is due to the fact that, for 11 of the 24 subjects in the experimental group, the rectal temperature never reached the equilibrium limit (38°C) even at 1.2 P4SR, whereas most subjects exceeded this limit in Löfstedt's study. When this occurs, the sensitivity of the sweating mechanism decreased (Wyndham 1965). Consequently, the relation between rectal temperature and sweat rate was best described by a curvilinear regression equation in Löfstedt's study.

For skin and mean body temperature, the results agreed with those reported for rectal temperature.

DISCUSSION OF PHYSIOLOGICAL DATA

Practical proposals with respect to physiological strain

The rectal temperature, pulse rate, and sweat rate in the three environments agree well with data on children's reaction to heat stress by Löfstedt (1966). The middle climate—27°C ET or 0.6 P4SR—, as intended, gave physiological strain values midway between the ordinary values of the thermally neutral reference climate—24°C ET or 0 P4SR—and those obtained in the hottest climate—29°C ET or 1.2 P4SR.

At 1.2 P4SR, the mean of the rectal temperature was raised to 38°C and was at the equilibrium limit (Löfstedt 1966). This means that the evaporative cooling effect of sweating was hardly large enough to maintain the rectal temperature constant. An increase in body temperature at that strain level would probably not have been counteracted by an increase in sweat secretion. Thus a further increase in climate load would have driven the body temperature out of control for an increasing number of subjects. Thus this environment—29°C ET or 1.2 P4SR—can be regarded as the maximum tolerable for prolonged heat exposure.

A thermal load of 1.2 P4SR or more is to be avoided because it cannot be tolerated for prolonged exposure; a heat stress exceeding 1.2 and even 0.6 P4SR should also be avoided for hygienic reasons. As Table 15 shows, the sweat rate, $\text{g/m}^2/3\text{h}$, was compared to the thermally neutral condition at 0 P4SR, three times higher at 0.6 P4SR, and five times higher at 1.2 P4SR. If the ventilation system is inefficient—as often seems to be the case in Swedish schools (Boysen *et al.* 1967a)—the increased sweat rate could manifest itself in two ways:

a) The intensity of the body odour will increase and, at least for unadapted subjects, give rise to annoyance;

b) the increased sweat rate increases the humidity of the air and can create a less comfortable climate. A high degree of humidity at normal or high room temperatures is accompanied by feelings of discomfort and stuffiness.

The relation between exposure duration and degree of physiological strain

Rectal temperature

The results clearly indicated that the effects of heat load on the thermoregulatory system appeared early and reached almost full strength already during the first hour of exposure. The increase in rectal temperature from the first hour of exposure to the second and from the second to the third at 0.6 P4SR—about $0.04^{\circ}\text{C}/\text{h}$ —and at 1.2 P4SR—about $0.06^{\circ}\text{C}/\text{h}$ —was only about 1/10 of the initial increase, i.e. the increase that occurred during the first hour of heat exposure (see Figure 8 a).

The increase in rectal temperature occurring within the trials could partly be attributed to the diurnal rhythm of the body temperature. According to Green (1966, p. 95) the body temperature can vary about 2°C during the day and often reaches its peak late in the afternoon or in the evening. The total increase of 0.05°C during the three hours of exposure to the reference climate (see Figure 8 a) probably illustrates the variation due to this diurnal rhythm and can also be taken as an indirect indication of the sensitivity of the measuring procedure.

However, the increase in rectal temperature under

heat load was about 0.1°C from the first to the last hour of exposure, or twice as large as the increase at 0 P4SR. This bigger change of rectal temperature under thermal stress was found to be statistically significant during the second hour of exposure (see Figure 8 a). Thus it can be concluded that the increases in rectal temperature from the first to the third hour in heat load reflected not only changes due to the diurnal rhythm, but also the fact that the physiological strain, with respect to deep body temperature, was slightly raised after the marked initial rise, although the environmental temperature stress remained constant. The heat gain per hour was greater at 1.2 P4SR than at 0.6 P4SR.

Pulse rate

Contrary to the rectal temperature results, the change of pulse rate indicated unchanged physiological strain during exposure to the hottest climate (see Figure 8 b). In the middle climate and the reference climate, the pulse rate even decreased from the first to the last hour of exposure. However, as previously mentioned, the pulse rate at 0 P4SR was above the usual resting level.

As is well known from studies of the physiology of emotions, the pulse rate will increase as a function of psychological stress and also of thermal stress. Thus it seems reasonable to suggest that the unusually high resting level of pulse rate was caused by anxiety and tension due to:

- a) the attachment of the physiological measuring devices immediately before the exposures;
- b) motivation to perform as well as possible on the performance tasks during the exposure.

As time passed during the exposure, the strain of the

psychological factors grew less, the subjects became adapted to the experimental situation, and the pulse rate decreased at 0 and 0.6 P4SR. However, at 1.2 P4SR the heat load increased so much that the resulting rise in physiological strain was no longer counteracted by the decreasing psychological strain, as was the case at the two other conditions with less thermal stress. Accordingly, the pulse rate remained unchanged.

As a consequence of this general sensitivity of pulse rate to stressors, it is concluded that the pulse rate must be considered an inadequate indicator of physiological strain under thermal load if the individual, at the same time, is subjected to psychological stress. Under these conditions, the rectal temperature should be used for measurements of the physiological strain, as recommended by Löfstedt (1966), on the basis of analyses of only physiological factors.

Gross sweat rate

Concerning gross sweat rate, g/h, as an indicator of physiological strain, no consistent relation was found between this measure and exposure duration, except a statistically significant increase during the second hour in the warmest climate. Moreover, in all climates, it was impossible to predict gross sweat rate during the second and third hour from knowledge of its value during either the first or the second hour of exposure, as was the case for rectal temperature and pulse rate. Nor was it possible to predict gross sweat rate under heat load from its resting level in the reference climate, or at 1.2 P4SR from its value at 0.6 P4SR.

The great intra-individual variation in gross sweat

rate within and also between the investigated climates can be explained by at least three facts:

a) It is reasonable to suggest that the gross sweat rate, g/h, recorded without consideration of the subject's body surface should be less reliable than the sweat rate, $\text{g/m}^2/3\text{h}$ (see Table 15). According to the laws of physics, the evaporative cooling effect of a given amount of sweat is not the same for a large and tall subject as for a small and short one.

b) The hourly recordings of gross sweat rate were made in the climate chamber by means of a less accurate weighing-machine (sensitivity not better than ± 50 g) than that used outside the chamber for recording the total amount of sweat produced during three hours of heat exposure (sensitivity ± 25 g)..

c) In the thermally neutral climate, the weight loss depended not only on evaporation by sweating, but also on evaporation from the lungs. The evaporated amount of water from the lungs at rest is approximately 20 g/h, irrespective of the climate conditions (Green 1966, p. 95). As the evaporation from the lungs thus remains almost constant in different climates, the total ordinary weight loss in a thermally neutral climate cannot be used for prediction of heat-induced weight loss.

Consistency and change in thermoregulation

The analysis of correlation and regression showed that although

a) the absolute degree of physiological strain was definitely raised from the 0 to 0.6 and further on to 1.2 P4SR for all strain measures and

b) the rectal temperature increased from hour to hour under heat load, the relative degree of physiological strain for each individual was rather unvaried, except for gross sweat rate, g/h. This means

that the physiological strain reaction, with regard to the measures of rectal temperature, pulse rate, and sweat rate, $\text{g/m}^2/3\text{h}$, can be considered characteristic for the heat exposed individual. Characteristic in the sense that, within the investigated temperature range, some subjects, irrespective of the degree of thermal stress, were more sensitive to the heat load and showed stronger thermoregulatory reactions than other subjects. Thus it seems reasonable to suggest that the thermoregulatory function is a constitutional characteristic of the subject.

Although an inter-trial consistency was found for all physiological strain measures (except gross sweat rate) it should be noted that this does not exclude the possibility of a change in the interaction pattern between the strain measures. On the contrary, such a change is most probable when the thermal equilibrium limit is reached, and an increase in rectal temperature can no longer be counteracted by an increase in sweat production. Wyndham (1965) and Löfstedt (1966) showed that, at higher body temperatures ($>38^{\circ}\text{C}$), there is a decline in the sensitivity of the sweating mechanism to a body temperature increase.

The relation between rectal temperature and sweating

As rectal temperature and sweat rate both increased under heat load but still did not correlate with each other, it shows that these strain measures reflect different aspects of thermoregulation (cf. below, Statistical techniques for analysis of the relation between physiological strain and performance). As pointed out in the introduction, rectal temperature is a controlled physiological variable, whereas sweating is a compensatory activity or a controlling reaction of the thermoregulatory system. As a

compensatory activity, sweating will be the best physiological heat stress index. An increase in thermal load will cause a rise in the deep body temperature; this in turn will be counteracted and controlled by an increase in sweating, provided the sweating has not already reached its absolute limit.

Intra-individually, the two aspects of thermoregulation are interdependent and correlated. Why then was a zero-correlation obtained? This can be explained in at least three ways:

a) As has previously been emphasized, the reliability of gross sweat rate, g/h, was not satisfactory.

b) Although the measures of rectal temperature and gross sweat rate refer to the same period of time, they do not do so in the same way. Whereas gross sweat rate showed degree of dehydration per hour, rectal temperature indicated deep body temperature at the end of each hour. The measure of gross sweat rate might have compared more with rectal temperature had it been expressed as a time-averaged temperature. None the less gross sweat rate was an integrated measure, whereas rectal temperature was a time-sampled measure.

c) The sensitivity of the sweating mechanism shows great inter-individual variation. The sweating threshold and the absolute limit of sweating differ among subjects. This means that if two subjects were characterized by the same slightly raised rectal temperature, one might have exceeded his sweating threshold, but not the other. At the same sweat rate, one might be able to maintain thermal equilibrium, i.e. the evaporative cooling effect would be sufficient to control the environmentally induced body temperature increase, whereas the rectal temperature of the other subject was out of control and was steadily rising. The thermal equilibrium limit, with respect to rectal temperature (38°C), was indeed exceeded by 13 of the 24 subjects in the experimental group.

PSYCHOLOGICAL DATA

Pre-exposure results: ability, personality, and other
individual characteristics

This section and the next present data related to subjects and tasks *per se*. This is essential for the explanations and conclusions presented in connection with the analysis of the experimental data obtained under thermal exposure of the subjects. The reader who is uninterested in the subject and task characteristics *per se* should skip these sections and continue reading the section headed: Experimental group: Mental performance changes - main results.

On the WIT II, DBA:8A (addition), and DBA:9A (multiplication), the observed means and variances were in accord with the standardization data. This indicated that the investigated sample was representative of the Swedish population of ten-year-old school children with respect to intelligence and numerical ability.

There were no statistically significant differences between the control and the experimental group on the WIT II, DBA:8A, 9A, Partington 1, 2, or the CWT, nor were there any statistically significant differences between the subgroups within the experimental group. This means that differences in mental performance under thermal load between the subgroups within the experimental group cannot be referred to differences in pre-exposure ability, as such differences did not exist and the subgroups were alike in this respect.

Subjects with high scores on the WIT II also tended to have high scores on the other tests (addition: $r=.34^*$; multiplication: $r=.37^*$; Partington 2: $r=.38^*$) except Partington 1. The two numerical tasks were strongly associated ($r=.80^{***}$); the correlation between the two Partington tests was slightly lower ($r=.58^{***}$).

In the experimental group, proportionally more subjects, characterized by a dissociative adaptation pattern in CWT, had low mental (WIT II) capacity compared with the stabilized ones. Dissociative subjects also tended to perform worse on all the pre-exposure tests and this tendency was significant on the two numerical tasks, according to χ^2 -testing of contingency tables. The cumulatives did not differ from the stabilizers regarding pre-exposure performance.

A check of the distribution of subjects with a high degree of physiological strain under heat load showed that neither ability nor personality factors were associated with final rectal temperature. Accordingly,

performance differences under thermal stress between subjects stratified with respect to these factors could not be referred to different degrees of physiological strain.

There were no significant differences between the control and the experimental group concerning answers to pre-exposure interview questions about clothing indoors and outdoors, perceived temperatures at home and in school, or preference for and frequency of sun-bathing and sauna bathing. Both groups reported that they preferred to wear "too much" rather than "too little" clothing outdoors. Indoors, more children preferred a woollen sweater than a shirt or blouse. There was a significant change from lighter clothing at home to heavier in school, probably because of a lower perceived temperature in school than at home. However, the school climate was not rated cool.

Analysis of the reported change of clothing with regard to intellectual ability and personality indicated that the change was statistically significant for subjects scoring below the intelligence test median and those with a dissociative (D_k) adaptation pattern in CWT; for cumulatives (C_k), the change approached the significant. High intelligence test scorers and stabilizers did not report change of clothing to any great extent.

In the experimental group, about 65% used sauna bathing and 65% sun-bathing. Among the sun-bathers, only about 10% reported sweating. Thus it can be concluded that, even if a number of children were sometimes heat exposed, they were not physiologically heat acclimatized to any great extent.

Control group data

The performance measures proved to be approximately normally distributed when plotted on normal-probability paper, except error percentage on the numerical tasks, which followed the Poisson distribution. All versions of the tasks were parallel, (equal means and variances) except the CFF, on which trials beginning from fusion, according to expectation, had a higher mean frequency than those beginning from flicker. The reliability was satisfactory—mostly .70 or better—except Partington 2 and Auditory Startle Response. As these tasks were considered measures of cue-utilization and attention, low coefficients of reliability are to be expected.

Between learning and memory, there was a significant correlation of about .75 indicating good retention at rapid learning, and *vice versa*. The number of calculated items and the error percentage in the multiplication

task correlated about $-.70$, which means that rapidly multiplying subjects were able to multiply correctly too, and *vice versa*. No corresponding correlation was found in the addition task, which indicates that fast and slow adding subjects were equally accurate. The average error percentage was about 10% and only about 3% in the addition task. The low error percentages suggest that either the tasks were simple—at least the addition task—or the children gave priority to accuracy rather than speed. Because of the low average error percentage, there was no significant correlation between the two numerical tasks with respect to accuracy. However, the correlation of the measure of speed on the two tasks was significant, about $.85$, which agrees with the pre-exposure results. The same degree of association was found between raw score and bonus score on the APT, but the bonus score was slightly more reliable and and sensitive than the very low raw score. The correlation between Partington 1 and 2 varied from $r = .80^{***}$ at the first trial to $r = -.36$ at the second and $r = .59^*$ at the third.

Of the performance tasks, only learning and memory were related to WIT II. The regression of learning performance on intelligence was most pronounced at the first trial ($\beta = 2.01^*$) and grew weaker at the third trial ($\beta = .84^*$). This means that the differences in learning performance between more and less intelligent subjects became less, the more the subjects were trained. It also indicates that a transfer or learning-how-to-learn effect on the learning tasks was greatest for low scorers on the WIT II. However, no significant correlation between intelligence and transfer effects was found.

Experimental group: Mental performance changes—main results

With reference to Figure 6 Question 1, Table 16 and Figure 9 present mental performance changes under heat stress for the experimental group.

Learning

Temperature effects

Under thermal stress, the deterioration of performance

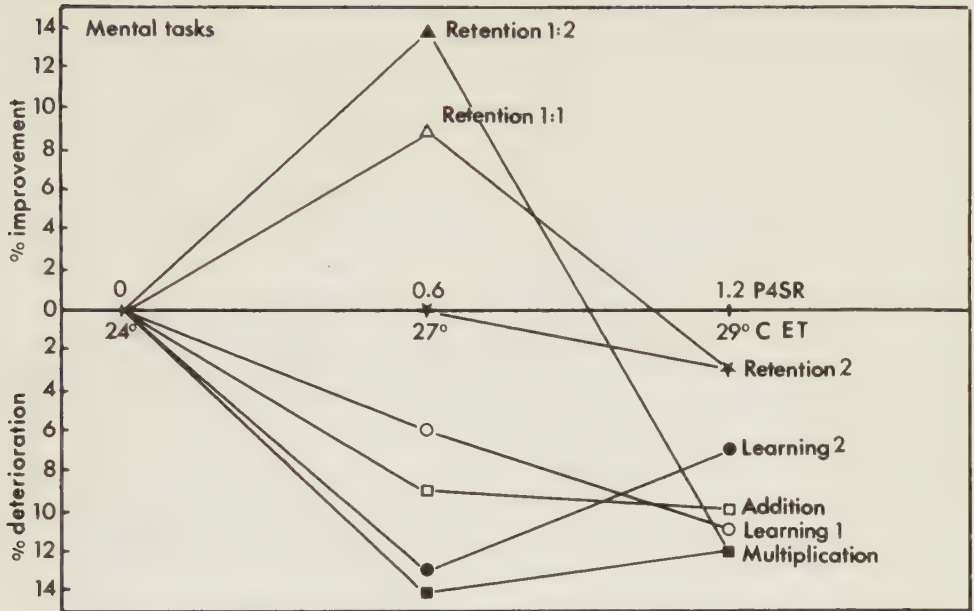


Figure 9. Performance changes on mental tasks for the experimental group under heat load.

in the two Learning tasks averaged 10%. However, either this climate effect or the sequence effect was statistically significant, as indicated by the analysis of variance (see Appendix Tables 5, 6), but the probability that Learning would be reduced by chance in each of the two tasks at both 0.6 and 1.2 P4SR, as predicted, is only $(1/2)^4$, corresponding to 6.25%.

Interaction effects between temperature and sequence

A significant interaction effect between the climates

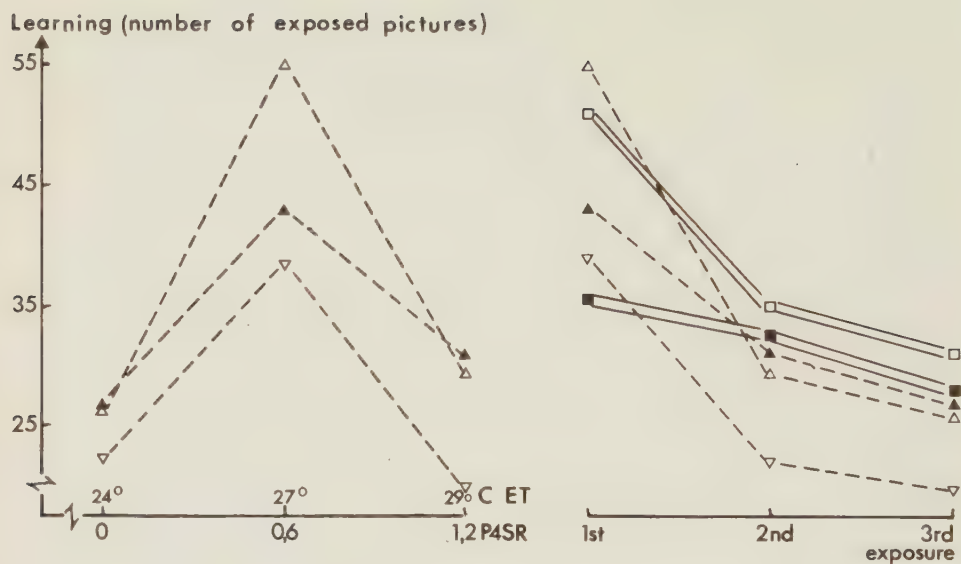


Figure 10. Significant interaction patterns on Learning 1 and 2 [Experimental group: Learning 1: $\Delta-\Delta$ climate sequence 6 (0.6-1.2-0 P4SR); Learning 2: $\blacktriangle-\blacktriangle$ climate sequence 6; $\nabla-\nabla$ climate sequence 2 (0.6-0-1.2 P4SR). Control group: Learning 1 $\square-\square$; Learning 2 $\blacksquare-\blacksquare$].

and their order or presentation appeared in both tasks; but for Learning 1, it must be interpreted with care, as the within-subject component consisted of heterogeneous variances (the main effect of temperature was checked and its non-existence was confirmed by Friedman's two-way analysis by ranks). Consequently, a strict conservative test procedure was adapted: this means that a simple main effect was considered significant only if two test conditions

were fulfilled: a) the F-ratio with the pooled residual (within-subject) component as error term; b) the F-ratio with the specific residual variance as error term; both should exceed their proper critical values (see further text to Appendix Table 5).

According to this procedure, significant simple main effects were noted on both tasks only for subjects meeting the 0.6 P4SR condition at their first exposure, as Figure 10 shows (see also Appendix Tables 5, 6). Although subjects with other orders of presentation of the climates also tended to perform worst at their first trial—occurring in the reference climate or at 1.2 P4SR—the interaction and simple main effects for these experimental subgroups were not statistically significant.

The relation between change of performance on the two Learning tasks

As Table 16 shows, the performance deterioration in Learning 1, occurring during the first hour of heat exposure, did not differ from the deterioration in Learning 2, occurring during the last hour of exposure, either at 0.6 or 1.2 P4SR. Nor was there any statistically significant difference between the climates with respect to transfer from Learning 1 to Learning 2 within each condition, i.e. the transfer within trials was not heat influenced.

These results indicated conclusively that the heat stress influenced the Learning performance with almost full strength already during the first thirty minutes of exposure and then remained constant. No progressively increasing effects on performance appeared. As there was a strong correlation within each stress condition between the two Learning tasks with regard to performance change (0.6 P4SR: $r = .69^{**}$;

1.2 P4SR: $r=.75^{xxx}$), it was clearly borne out that subjects who were performance affected by heat during the first hour of exposure were adversely affected also during the last hour.

Memory

Temperature effects

Contrary to expectation, an inverted U-shaped relation was found between memory performance and heat stress, especially at Retention measurements 1:1 and 1:2, as Table 16 and Figure 9 show. Compared with the reference climate, the Retention was about 10% better at 0.6 P4SR and about 10% worse at 1.2 P4SR. Although none of these performance changes under heat load were statistically significant, the two stress climates differed in Retention 1:2 (see Appendix Tables 7, 8, 9). In this task, the quadratic trend illustrated in Figure 9 also proved significant.

The probability that the inverted U-shaped trend would occur in each of the three memory tasks by chance is $(1/4)^3$, corresponding to 1.5%. Therefore the quadratic trend must be considered reliable.

Interaction effects between temperature and sequence

Figure 11 illustrates a significant interaction effect in Retention 2 between the climates and their order of presentation. The analysis of simple main effects indicated that performance differences between the climate sequences appeared only at 0.6 P4SR (see Appendix Table 9). As was found for the Learning tasks, subjects exposed to that condition at their first trial performed worse than subjects exposed to the middle climate at their second or third exposure. For

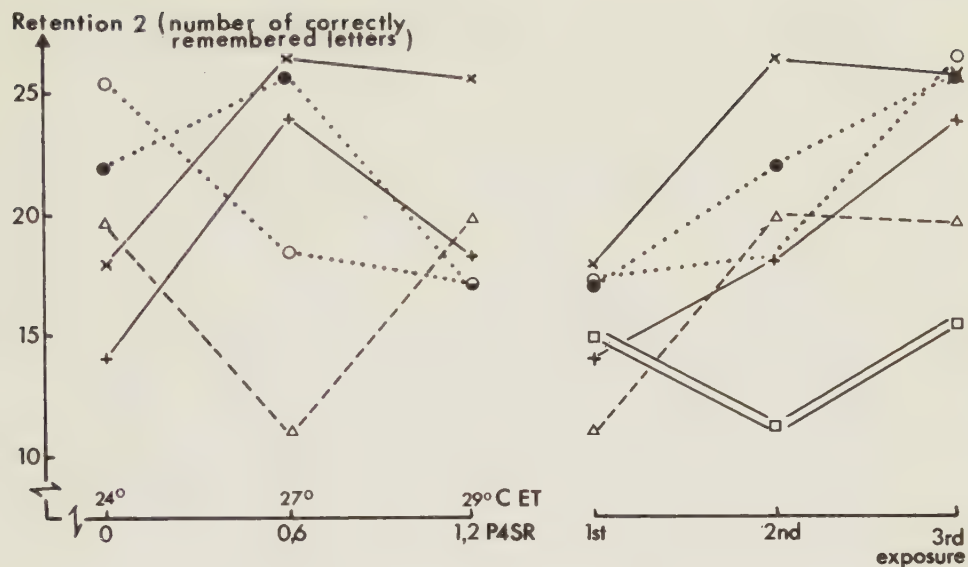


Figure 11. Significant interaction patterns on Retention 2 [Experimental group: +—+ climate sequence 1 (0-1.2-0.6 P4SR; O—O climate sequence 3 (1.2-0.6-0 P4SR); x—x climate sequence 4 (0-0.6-1.2 P4SR); ●—● climate sequence 5 (1.2-0-0.6 P4SR); Δ—Δ climate sequence 6 (0.6-1.2-0 P4SR). Control group □—□].

the latter group, the Retention was in fact best at 0.6 P4SR, according to an analysis of simple main effects between climates within climate sequences, a result which agrees with the inverted U-shaped curve appearing in Retention 1:1 and 1:2.

The analysis also showed that all subjects performed worst in the condition they were first exposed to. However, according to the control group data, no trend

or carry-over effect from trial to trial was to be expected on Retention 2, as is evident from Figure 11. Furthermore, no transfer tendency occurred either in Retention 1:1 or 1:2, neither having a significant interaction between climate sequence and temperature.

The relation between change of performance in the measurements of Retention

Although the performance decreased from Retention 1:1 to 1:2 in all conditions, no progressively increasing heat-induced effects on memory were found, as Table 16 shows (cf. the inexistent heat effect on transfer from Learning 1 to 2). Moreover, the difference in the heat-induced memory change between Retention 1:1 and 1:2, after twice as long exposure, was not statistically significant either at 0.6 or 1.2 P4SR. This indicated that the heat effect asserted itself in the memory performance during the first 85 minutes of exposure and did not subsequently increase.

A positive correlation between the deviation measures of Retention 1:1 and 1:2 (0.6 P4SR: $r=.59^{**}$; 1.2 P4SR: $r=.47^*$) showed, as was found in the Learning tasks, that subjects mentally affected by the thermal load during the first part of the exposure were also affected during the second part. Contrary to expectation, neither of these measures was associated with the deviation measure of Retention 2.

The memory changes under heat load occurred independently of the performance changes in the Learning tasks, except the changes in Retention 2 and Learning 2 at 0.6 P4SR ($r=.58^{**}$).

Arithmetic

Speed

Statistically significant decreases of about 10% in the number of calculated items were noted at 0.6 and 1.2 P4SR on both numerical tasks (see Table 16, Figure 9, Appendix Tables 10, 11). The trend analysis indicated that the negative linear trend illustrated in Figure 9 was statistically significant for both tasks. In the Multiplication task the quadratic trend was also significant, but this trend accounted for only 35% of the temperature variance (see Appendix Table 11).

As the F-test is robust with respect to violation of the assumption of homogeneity of error variance, especially if the n's are equal, the climate sequence mean square of Multiplication was tested against a pooled error term of heterogeneous between-subject variances (see Appendix Table 11). In both numerical tasks and in all the other tasks, the main effect of climate sequence was far from statistically significant.

A heat-induced change of the number of calculated items in the Addition task was slightly associated with a corresponding change in the Multiplication, but the correlation was significant only at 1.2 P4SR ($r=.37^*$).

Accuracy

According to non-parametric testing, the measures of accuracy were unaffected in the Addition task, but for the Multiplication task, a non-inverted U-shaped heat stress-performance trend was found (see Table 16). The lowest accuracy was noted at 0.6 P4SR, the error score at this condition being different from and higher than that noted at 1.2 P4SR.

Climate condition		24°C ET - O P4SR	27°C ET - 0.6 P4SR	29°C ET - 1.2 P4SR		
Task		dev. in %		abs. of O P4SR	dev. in %	$r_{0.6 \times 1.2}$
		abs.	abs. of O P4SR			
Learning 1		28.4 ⁺ 16.7	30.1 ⁺ 17.8	31.5 ⁺ 25.6	-11%	.19
Learning 2		24.0 ⁺ 14.2	27.0 ⁺ 16.2	25.6 ⁺ 16.0	-7%	.38*
Retention 1:1		19.2 ⁺ 7.5	20.9 ⁺ 6.8	18.7 ⁺ 6.7	-3%	.56**
Retention 1:2		14.8 ⁺ 7.7	16.9 ⁺ 6.4	13.0 ⁺ 6.4	-12%	.68***
Retention 2		20.5 ⁺ 7.5	20.5 ⁺ 8.1	19.8 ⁺ 8.5	-3%	.46*
Addition (Σ calc. items)		121.4 ⁺ 48.9	110.5 ⁺ 58.9	109.0 ⁺ 47.4	-10%	.32 ^o
Multiplication (")		78.8 ⁺ 41.4	67.6 ⁺ 37.6	69.0 ⁺ 35.0	-12%	.47*
Addition (error perc.)		7.3 ⁺ 10.6	6.8 ⁺ 12.2	5.8 ⁺ 6.4	21%	.59**
Multiplication (")		10.2 ⁺ 10.6	14.2 ⁺ 16.5	11.4 ⁺ 13.3	-12%	.36*

Table 16. Mental performance in absolute and deviation score in the experimental group—mean—standard deviation. The table also shows the product-moment correlation (Spearman's rank correlation for the accuracy measure on the numerical tasks) between the deviation score at 0.6 and 1.2 P4SR (for units of measurement see text; * denotes 0.1, ** denotes 0.05, *** denotes 0.01, denotes 0.001, statistical significance; asterisk above absolute score indicates difference between 0.6 and 1.2 P4SR; asterisk above deviation score indicates difference between the reference climate and 0.6 or 1.2 P4SR; all test were two-tailed except tests of coefficients of correlation which were one-tailed).

Subjects with a heat-induced change of accuracy in the Addition task at 0.6 P4SR had a corresponding change in the Multiplication task ($r=.53^{**}$), whereas no relation was found between the two tasks at 1.2 P4SR (cf. the change in the number of calculated items).

Experimental group: Perceptual performance changes—
main results

With reference to Figure 6 Question 1, Table 17 and Figure 12 present perceptual performance changes under heat stress for the experimental group.

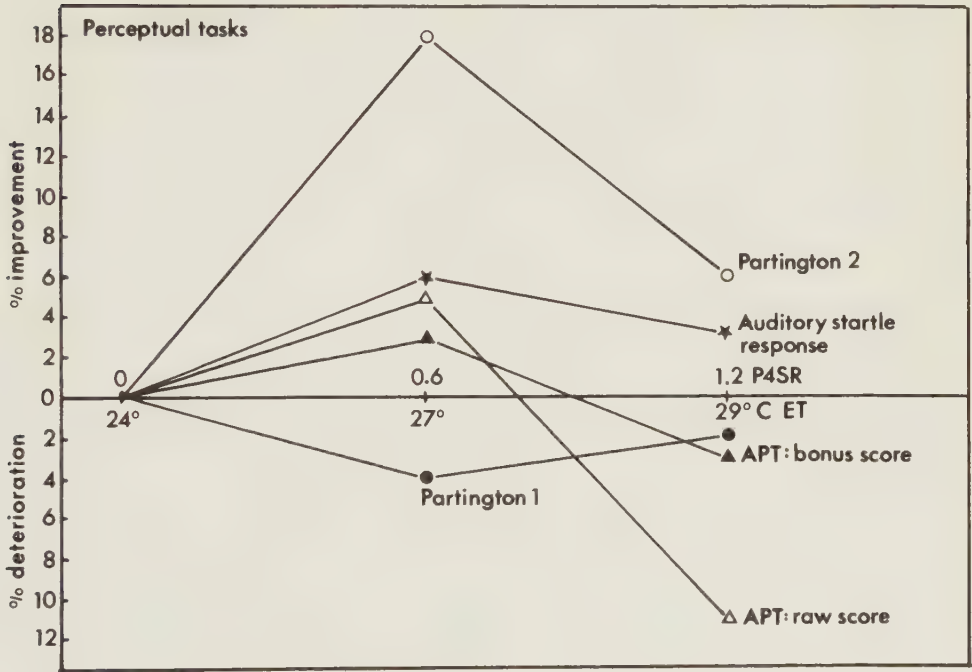


Figure 12. Performance changes on perceptual tasks for the experimental group under heat load.

Gestalt perception—APT

Temperature effect

The gestalt perception task—APT— appeared to be difficult for both the experimental and the control group, as indicated by an average raw score of about 2.5 out of 9 possible. The scope for deterioration was accordingly very restricted, and no statistically significant temperature effect was found for either raw score or bonus score (see Appendix Tables 12, 13).

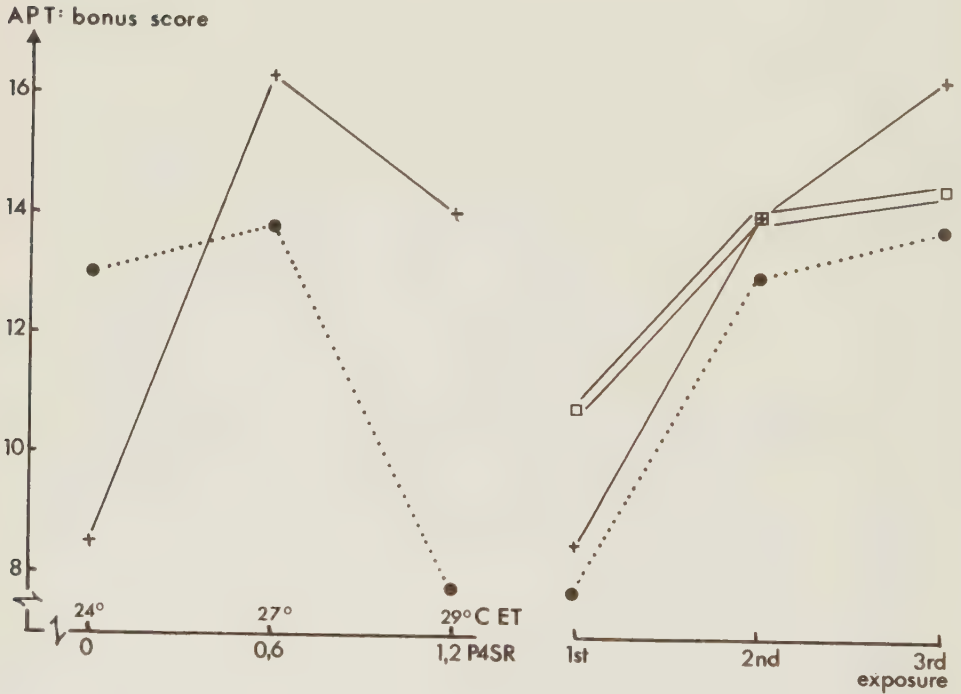
Interaction effects between temperature and sequence

Figure 13. Significant interaction patterns on APT [Experimental group: +—+ climate sequence 1 (0-1.2-0.6 P4SR); ●—● climate sequence 5 (1.2-0-0.6 P4SR). Control group: □—□].

The interaction effect between the climates and their order of presentation was significant beyond the 0.01 level for raw score and beyond the 0.001 level for bonus score, as Figure 13 shows. Tests of simple main effects showed that the best performance under thermal load at 0.6 or 1.2 P4SR was found for subjects meeting the neutral climate at their first exposure. As is evident from Figure 13, the tests of simple mean differences also indicated that a substantial learning occurred from trial to trial, in accordance with the control group findings. However, this transfer appeared only for subjects exposed to 0 or 1.2 but not to 0.6 P4SR at the first trial (cf. the transfer effect in the two Learning tasks).

Auditory Startle Response

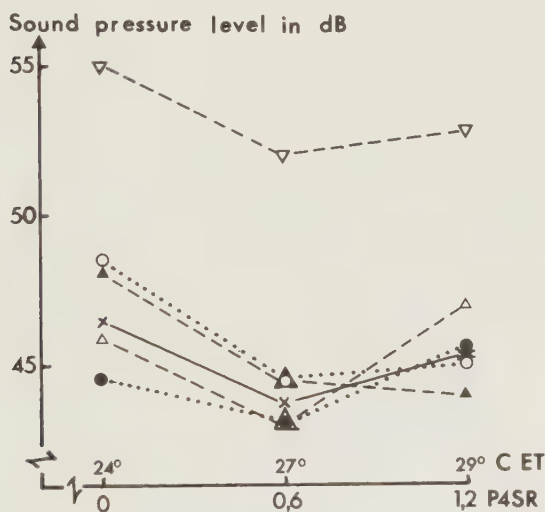


Figure 14. Sound pressure level eliciting a startle response in different climates (x—x total experimental group; o—o > WIT II m_d; •—• < WIT II m_d; Δ—Δ C_k; ▲—▲ D_k ▽—▽ S_k).

Figure 14 shows the sound pressure level at which the auditory signal elicited a startle response in different conditions. As it was impossible to observe any definite Auditory Startle Response for four of the 24 subjects in the experimental group, the data was analysed by conventional t-test for related observations. As the drop-out of subjects was evenly distributed among the climate sequences it was not thought to prevent or bias statistical testing.

The analysis verified the prediction and showed that the Auditory Startle Response was, on average, elicited by a weaker signal at 0.6 P4SR than at the neutral temperature, whereas the strength of the response eliciting a signal at 1.2 P4SR did not differ from either of the other conditions (see Table 17). As Figure 14 shows, the means form a tentative quadratic trend, with the weakest mean signal located at the middle climate.

Cue-utilization—Partington's Pathways Test

Partington 1

Partington 1 appeared, on average, to be rather insensitive to thermal stress, as Table 17 and Figure 12 show. However, the interaction effect between the climates and their order of presentation was found to be statistically significant (see Appendix Table 14). As Figure 15 shows, in three of the six climate sequences, the highest score was achieved at the last exposure and the lowest at the first exposure, irrespective of the climate load. Thus the interaction was probably more due to learning, as found for the control group, than to temperature. This interpretation of the interaction was considered most adequate, because the transfer was not restricted to sequences beginning or ending with a certain

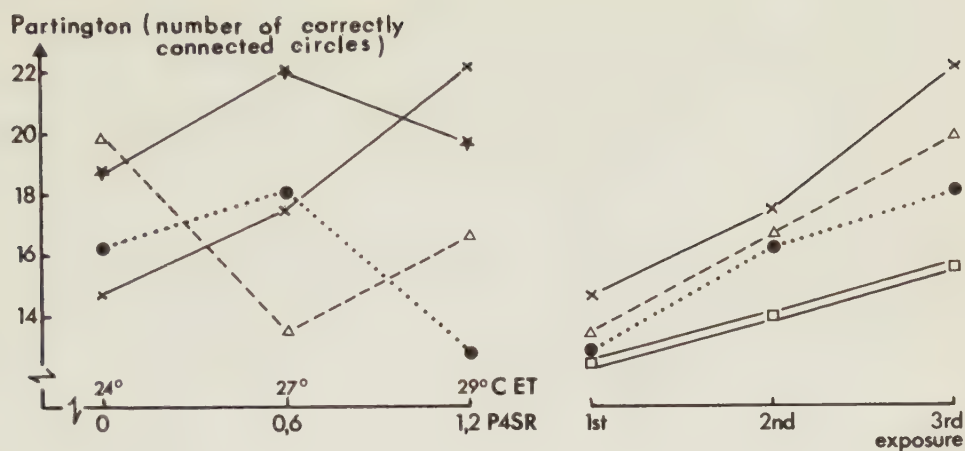


Figure 15. Significant interaction patterns on Partington 1 and quadratic trend on Partington 2 [Experimental group: Partington 1: x—x climate sequence 4 (0-0.6-1.2 P4SR); ●—● climate sequence 5 (1.2-0-0.6 P4SR); Δ—Δ climate sequence 6 (0.6-1.2-0 P4SR). Control group □—□. Total experimental group: Partington 2: ★—★].

climate condition, as previously was found to be the case for the Learning and Retention tasks, and also for the APT.

Partington 2

The main effect of temperature on performance in Partington 2 was statistically significant with the best performance (118%) at 0.6 P4SR compared with the reference climate. Thus, according to expectation,

Partington 2 showed a statistically significant inverted U-shaped relation to heat load (see Appendix Table 15); a relation also appearing in the Auditory Startle Response test and the memory tasks, especially Retention 1:2.

However, the performance change at 0.6 P4SR in Retention 1:2 was inversely associated with the change in Partington 2 ($r = -.49$). This indicated that subjects adversely affected in Retention 1:2 improved their cue-utilization performance.

According to expectation, the performance change in Partington 2 was negatively correlated with change of the signal strength that elicited the Auditory Startle Response ($r = -.47^*$). Improved achievement in cue-utilization at 0.6 P4SR was thus associated with increased reactivity to unexpected acoustic signals in the environment.

The interrelation between change of performance in Partington 1 and 2

The heat-induced performance changes in Partington 1 and 2 did not correlate in either of the stress conditions. This agreed with the absence of any correlation between the two tasks in the control group.

Critical flicker frequency—CFF

Table 17 shows that the mean frequency of CFF under heat load was only slightly affected, and no statistically significant temperature effect was found either in descending or ascending series.

Climate condition	24°C ET - P4SR	27°C ET - 0.6 P4SR	29°C ET - 1.2 P4SR	$r_{0.6 \times 1.2}$
Task	abs.	abs. of O P4SR dev. in %	abs. of O P4SR dev. in %	
APT: raw score	2.4 ⁺ 1.7	2.5 ⁺ 2.0	2.1 ⁺ 1.8	.57**
APT: bonus score	11.2 ⁺ 6.4	11.5 ⁺ 7.6	10.9 ⁺ 7.1	.58**
Auditory Startle Response	46.5 ⁺ 5.2	43.8 ⁺ 3.9	45.3 ⁺ 6.6	.41*
Partington 1	17.0 ⁺ 5.4	16.2 ⁺ 4.8	16.6 ⁺ 6.0	.38*
Partington 2	18.7 ⁺ 6.3	22.0 ⁺ 8.6	19.8 ⁺ 6.5	.46*
CFF: descending series	48.8 ⁺ 5.8	48.8 ⁺ 6.1	47.9 ⁺ 7.9	.57**
CFF: ascending series	43.3 ⁺ 5.6	43.5 ⁺ 7.0	44.0 ⁺ 6.3	.63**

Table 17. Perceptual performance in absolute and deviation score in the experimental group—mean—standard deviation. The table also shows the product-moment correlation between the deviation score at 0.6 and 1.2 P4SR (for units of measurement see text; * denotes 0.05, ** denotes 0.01 statistical significance; asterisk above absolute score indicates difference between 0.6 and 1.2 P4SR; asterisk above deviation score indicates difference between the reference climate and 0.6 or 1.2 P4SR; all tests were two-tailed except tests of coefficients of correlation which were one-tailed).

The relation between performance changes at 0.6 and 1.2 P4SR

The data for the Learning and Retention tasks, presented in Table 16, indicated that subjects adversely affected at the beginning of the heat exposure were also affected when their performance was measured at the end of the exposure. In addition to a study of the intra-trial consistency, the inter-trial consistency of heat-induced performance deterioration was also studied. The Spearman rank correlation was calculated between the deviation score at 0.6 and 1.2 P4SR; the last columns in Tables 16 and 17 show the correlation coefficients.

The analysis of correlation conclusively demonstrated that the relative degree of heat-induced performance changes is a consistent characteristic of the individual. If a subject is adversely affected at moderate thermal load, 0.6 P4SR, he will probably be so also when exposed to increased heat, 1.2 P4SR. There was a strong relation between performance change at 0.6 and 1.2 P4SR for almost all the tasks. The highest coefficients—about .60—were found for the first two Retention measurements and the APT. A not statistically significant correlation was found only for Learning 1, presented immediately after the subject's entrance into the chamber.

Performance changes as a function of physiological strain

In order to investigate which of the physiological strain variables—rectal temperature, pulse rate, and gross sweat rate, g/h—and which of the two ways of measuring these variables—absolute and deviation measures—were most closely related to performance changes under heat load, Spearman's rank correlation

Climate condition		27°C ET - 0.6 P4SR				29°C ET - 1.2 P4SR			
Physiological variable		gross				gross			
Physiological measure		rect.	temp.	pulse rate	sweat rate	rect.	temp.	pulse rate	sweat rate
		abs.	dev.	abs.	dev.	abs.	dev.	abs.	dev.
Learning 1		.37 x	.67 xx	-.07	-.44 x	.37 x	.10	.01 o	-.28 x
Learning 2		-.28	-.65	.03	-.21	.26	-.26	-.32	-.47
Retention 1:1		-.02	.01	-.06	-.26	-.27	-.45	-.01	.03
Retention 1:2		-.03 x	.12 xx	.24	.12 x	-.03	.04	.15 x	.16 xxx
Retention 2		-.35	-.63	-.17	-.41	.24	-.26	-.43 o	-.67
Addition (Σ calc. items)		-.06	-.06	-.25	-.24	-.25	-.08 x	-.32	-.32
Multiplication (")		.01	.19 x	-.21	.24 x	.16	.36	-.01 x	.14 o
Addition (error perc.)		-.16	-.43 x	-.22	-.37 o	-.09	.10	-.24	-.30
Multiplication (")		-.02 x	-.35 xx	.08	-.33 o	-.04	-.11	.07 x	-.17 o
APT: raw score		-.40 x	-.54 xx	-.16	-.28 x	.14	-.03	.18 o	-.32
APT: bonus score		-.43	-.64	-.17	-.37	.37	-.08	-.28	-.32
Auditory Startle Response		.07	.15 x	.19	-.21 xx	.08	.04	.20 xx	-.20 xxx
Partington 1		-.09	-.37	-.24	-.55 o	-.02 x	.14	-.50	-.65
Partington 2		-.12	-.21	-.24	-.28	.47	.24	-.11	.01
									-.14
									-.26

Table 18. Spearman rank correlation coefficients between physiological strain, recorded in absolute and deviation measures, and performance changes under heat stress. Positive coefficients indicate that high physiological strain was related to performance improvement; negative coefficients indicate an association between high physiological strain and performance impairment. All tests were one-tailed with expected negative coefficients for rectal temperature and pulse rate, respectively, and positive coefficients for gross sweat rate, g/h (o denotes 0.1, x denotes 0.05, xxx denotes 0.01, and xxx denotes 0.001 statistical significance).

coefficients, r_s , were calculated, as shown in Table 18.

Retention 1:1 and 1:2, speed in the numerical tasks, Partington 2, and Auditory Startle Response did not correlate consistently with any of the physiological strain variables, no matter how they were measured.

However, the correlation between the performance change in most other tasks and the deviation measure of rectal temperature was consistently high: r_s was $-.50$ or more negative. This indicated that the performance was more adversely affected the greater the physiological strain. According to expectation the rectal temperature was found to be that strain variable which for most of the psychological tasks correlated most closely with performance deterioration at both 0.6 and 1.2 P4SR, whereas the gross sweat rate, g/h, only in some cases at 0.6 and none at 1.2 P4SR was significantly related to performance improvement. The deviation measures of rectal temperature and pulse rate were definitely more closely associated with mental performance changes under heat load than the absolute measures, whereas for gross sweat rate, g/h, it was the absolute measure which correlated with performance changes.

The strength of association between physiological strain and performance change was not appreciably different for the two stress conditions, except that the gross sweat rate, g/h, was not related to performance changes at 1.2 P4SR. Thus it can be concluded that in most tasks the adversely performance-affected subjects under thermal load were characterized by increased pulse rate, and in particular increased rectal temperature, whereas no reliable relation was found between change of performance and gross sweat rate, g/h.

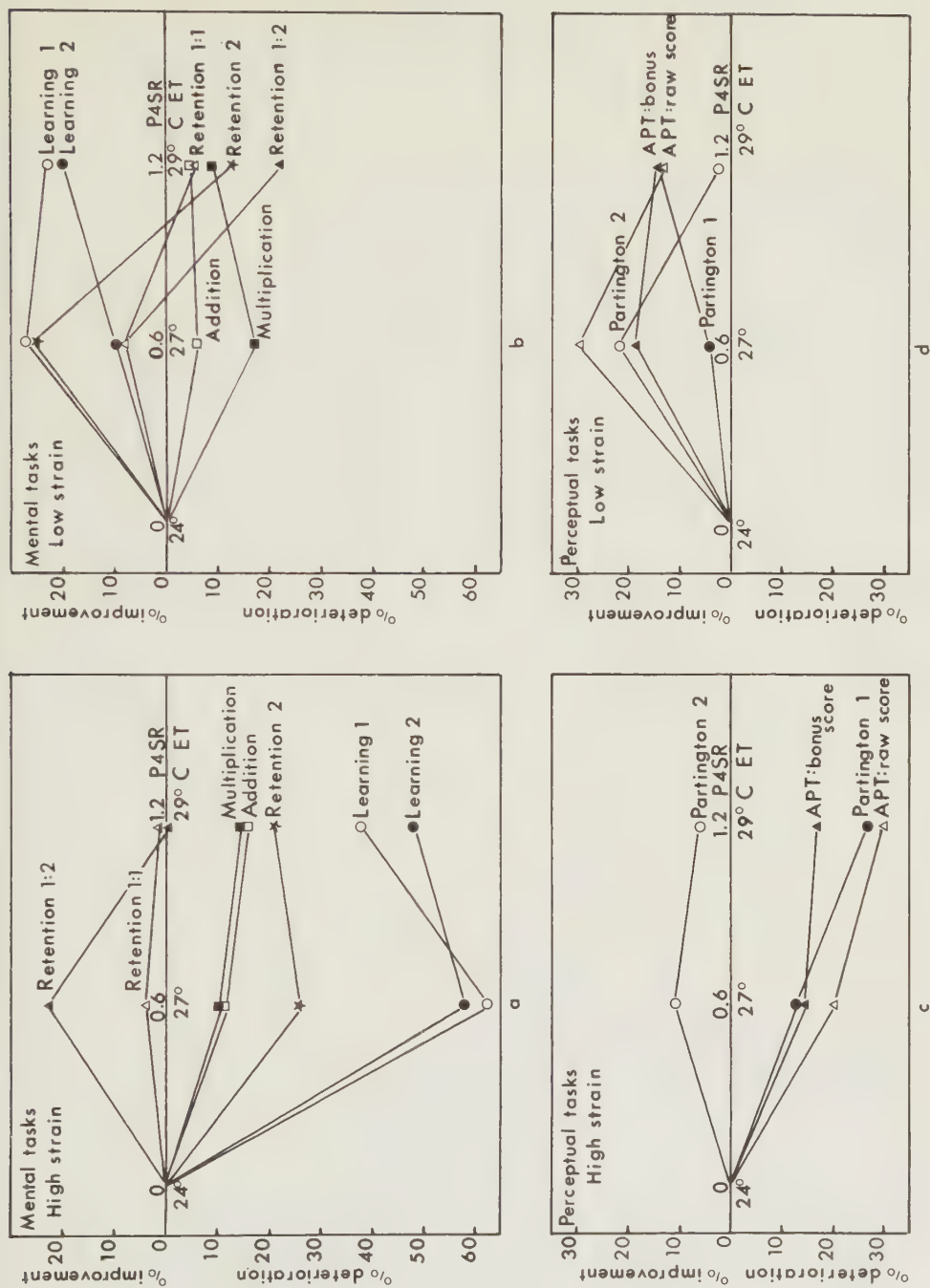


Figure 16. Performance changes on mental (16a,b) and perceptual (16c,d) tasks for subjects with rectal temperature deviation above (16a,c) and below (16b,d) the median value for each climate.

The relation between the deviation measure of rectal temperature and performance change—those variables that were most closely related—was further analysed for each climate condition by comparing performance changes of subjects characterized by an increase in rectal temperature above the median with subjects below the median increase in rectal temperature. Table 19 and Figure 16 provide the answer to Figure 6 Question 2 by presenting the mean change in performance for the two groups of subjects.

For those tasks in which the difference between the two groups was statistically significant—Learning 1 and 2, Retention 2, accuracy in the numerical tasks, Partington 1, APT: raw and bonus score—the performance of the most physiologically heat affected group seriously deteriorated—between 11% and 63%. Contrary to the physiologically affected subjects, the performance improvement of the less affected subjects was slight, and in some tasks, the improvement was statistically significant. Subjects with a rectal temperature deviation below the median changed for the worse only in the two numerical tasks at 0.6 and 1.2 P4SR, and in Retention 1:1 and 1:2 at 1.2 P4SR. Of these changes, the only significant one was noted at 0.6 P4SR with respect to the number of calculated items in the Multiplication task. However, it is noteworthy that, in each of these tasks, the average of the absolute performance score under heat load of the less affected group superseded the average of the most affected group. The heat-induced differences in performance change between the two strain groups were noted at both 0.6 and at 1.2 P4SR, although the performance improvement of the less physiologically affected group was less at 1.2 than at 0.6 P4SR.

The number of items attempted in the two numerical tasks decreased about 10% under the two stress conditions, independent of the rectal temperature;

Climate condition		27°C ET - 0.6 P4SR		29°C ET - 1.2 P4SR	
Rectal temperature deviation Task		< m _d	> m _d	< m _d	> m _d
Learning 1		^o 27% x	==# -63 x	23% x 20%	==# -38% o -48%
Learning 2		10%	==#		==#
Retention 1:1		9%	4%	- 6% o	1%
Retention 1:2		9% o	23%	-22% x	+ 0%
Retention 2		26%	==# -26% x	13%	==# -21% x
Addition (Σ calc. items)		- 6% x	-12% x	- 5%	-16% x
Multiplication (")		-17% o	-11% o	- 9%	-15%
Addition (error perc.)		56%	=θ= -39%	30%	=θ= 6%
Multiplication (")		13%	=θ= -80%	36%	=# -51% o
APT: raw score		30%	=θ= -20%	13%	=# -30% x
APT: bonus score		19%	=θ= -14%	14%	=# -17% x
Auditory Startle Response		$\frac{43.3 \text{ dB}}{47.2 \text{ dB}} \frac{(0.6 \text{ P4SR})}{(0 \text{ P4SR})} \frac{44.1 \text{ dB}}{45.9 \text{ dB}} \frac{46.2 \text{ dB}}{46.9 \text{ dB}} \frac{(1.2 \text{ P4SR})}{(0 \text{ P4SR})} \frac{43.6 \text{ dB}}{45.7 \text{ dB}}$			
Partington 1		4% x	=θ= -13%	14% x	=# -27% x
Partington 2		22%	11%	2%	6%

Table 19. Performance changes on the psychological tasks under heat load—in percentage of the average performance in the reference climate, 24°C ET, 0 P4SR—for subjects with rectal temperature deviations below and above the median for each climate condition (o denotes 0.1, x denotes 0.05, xx denotes 0.01, and xxx denotes 0.001 statistical significance in testing performance changes within each group; =θ= denotes 0.1, ==# denotes 0.05, =# denotes 0.01, and ## denotes 0.001 statistical significance in testing performance changes between groups; all tests were two-tailed).

thus the performance of both strain groups was approximately equally affected. For the other tasks in which the groups did not differ—Retention 1:1 and 1:2, Partington 2, and Auditory Startle Response—they both improved and changed their performance in an inverted U-shaped performance heat stress function.

Performance changes as a function of intellectual ability and skill

Intelligence

In most tasks, the performance change under heat load was not associated with general intellectual ability, as indicated by analysis of Spearman's rank correlation (r_s tested two-tailed) and by direct analysis of the achievement of subjects scoring below and above the intelligence test median. Table 20 presents these analyses answering Figure 6 Question 4.

Correlation coefficients approaching the significant were noted only in the two measurements of Retention 1 at 1.2 P4SR. They indicated tentatively that the more intelligent subjects were most adversely affected by the environmental heat. Retention 1:2 was at 1.2 P4SR the only task with a significant difference in performance change between the two intelligence groups. Despite a significant deterioration of 25%, the subjects above the WIT II median remembered more letters than subjects below the median. In fact, the low WIT II scorers did worse in most tasks in each climate.

A significant performance deterioration of about 10% under heat load appeared for both WIT II groups in the number of calculated items in the Multiplication task, and for low WIT II scorers also in the Addition task

Climate condition	27°C ET - 0.6 P4SR	29°C ET - 1.2 P4SR	$r_{0.6}$	$r_{1.2}$
Intelligence (WIT II) score	< m_d	< m_d		
Task	> m_d	> m_d		
Learning 1	-14%	6%	.18	.07
Learning 2	-12%	-14%	.05	.07
Retention 1:1	20%	1%	-.23	-.35°
Retention 1:2	28%	6%	-.13	-.40°
Retention 2	-13%	12%	.30	.12
Addition (Σ calc items)	-16%*	-4%	.17	-.22
Multiplication (")	-21%**	-10%*	-.02	-.07
Addition (error perc.)	-65%	67%	.27	-.07
Multiplication (")	-68%	-9%	.24	.32
APT: raw score	7%	3%	-.23	.03
APT: bonus score	3%	2%	-.06	.11
Auditory Startle Response	$\frac{43.0 \text{ dB}}{44.5 \text{ dB}}$	$\frac{44.5 \text{ dB}}{48.5 \text{ dB}}$	-.17	-.16
Partington 1	-11%	1%	.20	-.01
Partington 2	12%	23%	.22	-.02
CFF: descending series	-1%	1%	.19	.04
CFF: ascending series	1%	+ 0%	.00	.16

Table 20. Performance changes on the psychological tasks under heat load—in percentage of the average performance in the reference climate, 24°C ET, O P4SR, except for Auditory Startle Response with data presented in accordance with the formula reference condition— for subjects scoring below and above the intelligence test (WIT II) median. The table also shows Spearman's rank correlation between intelligence score and change of performance at 0.6 and 1.2 P4SR. Positive coefficients indicate that high intelligence was related to performance improvement; negative coefficients indicate an association between high intelligence and performance impairment (° denotes 0.1, * denotes 0.05, and ** denotes 0.01 statistical significance in testing performance changes within each group; =≠ denotes 0.05 statistical significance in testing performance changes between groups).

at 0.6 P4SR.

Skill

Tables 21, 22 and Figure 17 give the answers to Figure 6 Question 5 by presenting heat-induced performance changes for skilled and less skilled subjects. Skilled subjects, with a pre-exposure test performance above the median were most adversely affected by heat in the Multiplication task under both stress conditions (see Table 21). Although they showed a performance deterioration of about 20%—a change different from and greater than that noted for less skilled subjects—their performance under heat stress was about 70% better than the performance of the low scorers, as Figure 17 shows. Moreover, the error percentage in the Multiplication task was influenced in negative direction to a greater extent for the low scorers, but the differences between the two groups were not statistically significant. For subjects with low pre-exposure test score, the heat caused most deterioration in the Addition test.

Climate condition	27°C ET-0.6 P4SR		29°C ET-1.2 P4SR		r 0.6	r 1.2
Pre-exposure test score Task	< m _d	> m _d	< m _d	> m _d		
Addition (Σcalc. items)	-19%*	-3%	-12%	-10% ^o	.31	-.01
Multiplication (")	-8% ==	-17%**	-5% ==	-16%**	-.42*	-.37 ^o
Addition (error perc.)	-21%	43%	23%	19%	.14	-.07
Multiplication (")	-60%	-5%	-24%	7%	.38 ^o	.28
Partington 1	1%	-9%	7%	-9%	-.08	-.10
Partington 2	6%	32% ^o	4%	8%	.25	.03

Table 21. Performance changes on the numerical tasks and Partington's Pathways Test under heat load—in percentage of the average performance in the reference climate, 24°C ET, 0 P4SR—for subjects scoring below and above the pre-exposure test median. The table also shows Spearman's rank correlation between pre-exposure test score and change of performance at 0.6 and 1.2 P4SR (^o denotes 0.1, * denotes 0.05, and ** denotes 0.01 statistical significance in testing performance changes within each group; ~~==~~ denotes 0.05 statistical significance in testing performance changes between groups; all tests were two-tailed).

As the relation between heat-induced changes of mental performance and skill—skill measured as pre-exposure test performance—could be studied only for some tasks, this question was further studied by estimating skill for each task from the performance in the thermally neutral reference climate. Table 22 presents the results of this extended analysis.

In most tasks, there was a marked negative association between skill and performance change, indicating that skilled subjects—scoring above the median in the reference climate—were most adversely affected by the heat at both 0.6 and 1.2 P4SR. This association was most pronounced for the Retention measurements and for the measure of speed in the Multiplication task and accuracy in the Addition task. On these tasks, the impairment of the skilled subjects was significantly greater than for the less skilled subjects, who in fact improved their Retention 1:1 and 1.2 measurements at 0.6 P4SR. In this climate, the less skilled children also performed better in Partington

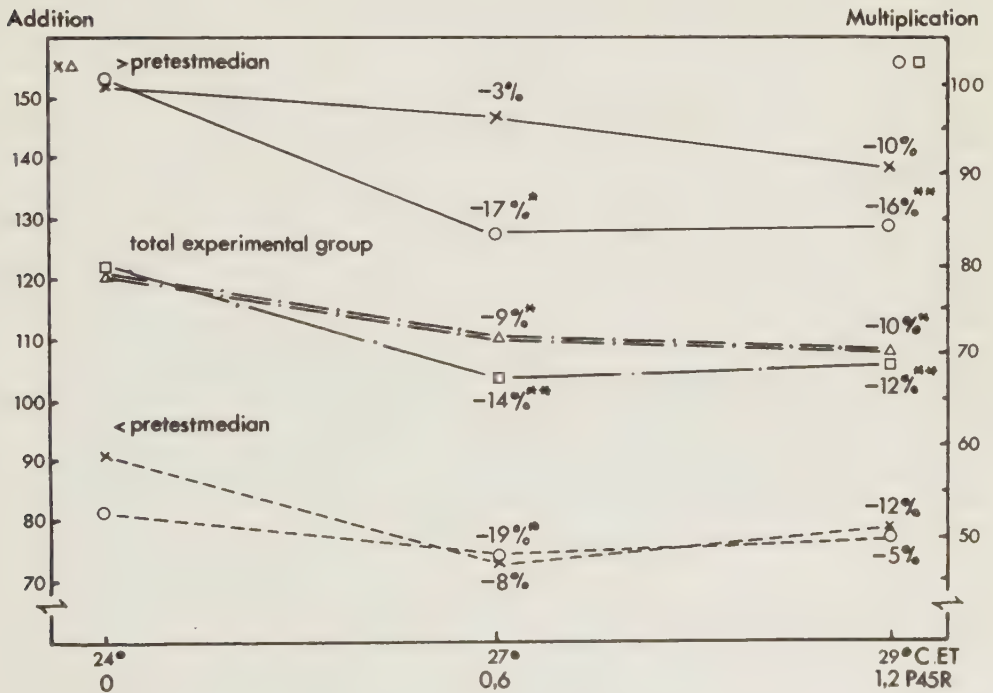


Figure 17. Number of calculated items on the addition and the multiplication task for the experimental group.

Climate condition	27°C ET - 0.6 P4SR		29°C ET - 1.2 P4SR	
Performance score in reference climate (0 P4SR) Task	< m _d	> m _d	< m _d	> m _d
Learning 1	6%	-35%	- 3%	-35%
Learning 2	- 3%	-34%	5%	-34%
Retention 1:1	[*] 41% ==≠	- 7%	[*] 22% ==≠	[*] -15%
Retention 1:2	^{**} 59% ==≠	- 4%	18% ==≠	[*] -24%
Retention 2	24%	-14%	-10%	⁺ 0%
Addition (Σcalc. items)	^o -18%	- 4%	-12%	^o -10%
Multiplication (")	-19% ==≠	^{**} -18%	-18% ==≠	^{**} -16%
Addition (error perc.)	10%	-22%	35% ==≠	-90%
Multiplication (")	-30%	-119%	- 5%	-69%
APT: raw score	117%	- 8%	33%	-16%
APT: bonus score	9%	- 1% [*]	9%	-10%
Auditory Startle Response	$\frac{43.6 \text{ dB}}{43.9 \text{ dB}}$ ==≠	$\frac{44.2 \text{ dB}}{52.5 \text{ dB}}$	$\frac{45.6 \text{ dB}}{43.9 \text{ dB}}$ ==≠	$\frac{44.2 \text{ dB}}{52.5 \text{ dB}}$
Partington 1	1%	- 8%	- 1%	- 2%
Partington 2	[*] 29%	10%	14%	⁺ 0%
CFF: descending series	⁺ 0%	⁺ 0%	- 5%	1%
CFF: ascending series	⁺ 0%	1%	4	- 1%

Table 22. Performance changes on the psychological tasks under heat load—in percentage of the average performance in the reference climate, 24°C ET, 0 P4SR, except for Auditory Startle Response with data presented in accordance with the formula $\frac{\text{stress}}{\text{reference}}$ condition—for subjects scoring below and above the performance score median in the reference climate (^o denotes 0.1, ^{*} denotes 0.05, ^{**} denotes 0.01 statistical significance in testing performance changes within each group; ==≠ denotes 0.05, ==≠ denotes 0.01 statistical significance in testing performance changes between groups; all tests were two-tailed).

2 than they did in the reference climate. A performance decrement for the less skilled subjects, which approach the statistically significant, appeared in fact only with respect to Addition speed at 0.6 P4SR.

However, it should be emphasized that although the performance of the skilled children was more adversely affected by the heat than the performance of the less skilled ones, the average level of performance for the skilled children under thermal load was in each task still far superior. Their performance in the two Learning tasks, in both measures of the two numerical tasks, and in the APT, was about twice as good as that of the less skilled subjects. This agrees with the previously presented data on skill measured by pre-exposure test performance.

As Table 22 shows, there was no difference in performance change between the two heat stress conditions. Both skilled and less skilled subjects were almost as much affected at 0.6 P4SR as at 1.2 P4SR.

Concerning the Auditory Startle Response test, it was found that subjects with a low auditory reaction threshold in the reference climate also reacted to weak signals when they were heat exposed, i.e. the intensity of the startle response eliciting signal was not changed. On the other hand, subjects with a high auditory reaction threshold in the reference climate were affected by the thermal stress. When they were heat loaded, a startle response was elicited by a signal of about the same low value as for the other subjects, i.e. a value corresponding to almost half of the sound pressure level that they reacted to in the reference climate.

Performance changes as a function of personality
characteristics

Climate condition	27°C ET - 0.6 P4SR			29°C ET - 1.2 P4SR		
Personality (CWT) classification Task	C _k	S _k	D _k	C _k	S _k	D _k
Learning 1	- 7%	17%	-36% °	-17%	13%	-15%
Learning 2	- 3%	7%	-37%	- 9%	- 8%	7%
Retention 1:1	18%	+ 0%	3%	- 1%	- 8%	- 2%
Retention 1:2	16%	14%	8%	-27%	-10%	- 9%
Retention 2	18%	9%	-13% *	8%	- 6%	-15% °
Addition (Σ calc. items)	- 5%	- 8%	-20%	- 4%	-13% °	-11% °
Multiplication (")	- 8%	== -22% *	== - 7%	- 9%	== -19% *	== - 7%
Addition (error perc.)	30%	19%	-29%	15%	40%	22%
Multiplication (")	4%	-47%	-80% *	3%	9%	-29%
APT: raw score	34%	- 5%	15%	- 4%	+ 0%	- 6%
APT: bonus score	15%	2%	- 5%	6%	1%	- 5%
Auditory Startle Response	43.0 dB	52.1 dB	44.5 dB	47.0 dB	52.9 dB	44.0 dB
Partington 1	46.0 dB	55.0 dB	48.0 dB	46.0 dB	55.0 dB	48.0 dB
	6%	-14%	- 5%	3%	- 8%	4%
Partington 2	14%	36%	9%	7%	13%	- 1%
CFF: descending series	1%	- 5%	3%	- 2%	- 8%	+ 0%
CFF: ascending series	1%	- 2%	4%	2%	- 2%	5%

Table 23. Performance changes on the psychological tasks under heat load—in percentage of the average performance in the reference climate, 24°C ET, 0 P4SR, except for Auditory Startle Response with data presented in accordance with the formula $\frac{\text{stress}}{\text{reference}}$ condition— for subjects with different personality classification (CWT) (° denotes 0.1, * denotes 0.05 statistical significance in testing performance changes within each group; == denotes 0.05, ==# denotes 0.01 statistical significance in testing performance changes between C_k or D_k and the reference group, S_k).

Table 23 shows heat-induced performance changes for subjects with different personality (CWT) classification. Although few findings were statistically significant, some tentative answers to Figure 6 Question 6 were given.

According to the outlined heat stress—strain—arousal—performance model, the effect of heat load at 0.6 P4SR seemed to be greatest for dissociative subjects (D_k) in most tasks, especially in the two Learning tasks and with respect to speed in the Addition test and to accuracy in the Multiplication test. However, it is to be noted that the dissociative subjects in these respects did not differ with statistical confidence from the stabilized ones. At 1.2 P4SR, no personality group tended to be consistently more affected than any other.

An exception to the trend in the middle climate was the measure of speed in the Multiplication task. In both stress conditions, a significant decrement averaging 20% was noted for the stabilizers (S_k). This performance change was twice as large as that noted for the other two groups, and the differences in change were statistically significant. However, the number of calculated items for C_k and D_k was only about 70% and 55%, respectively, of the performance of S_k . In fact, the S_k were superior in all tasks, irrespective of the room temperature.

The previously commented quadratic heat stress—performance trend, appearing in the memory measurements, the Partington 2, and the Auditory Startle Response, was found to be most marked for C_k , according to expectation, but it is to be emphasized that no heat-induced change was significant for either C_k or the other two groups.

Subjective report

According to the interview carried out immediately after each exposure, the subject's experience of the climate conditions was influenced by the heat, as Table 24 shows. In the neutral climate, about 85% reported that the exposure temperature was "just right", a proportion similar to that noted in the control group. At 0.6 P4SR, more than 50% changed their rating in the expected direction from "just right" to "too warm", "much too warm", or "hot" ($p < 0.01$). About 70% changed their rating in the warmest climate ($p < 0.001$); thus only 25% reported "just right".

No relation was found between thermal rating and final body temperature.

Climate condition Rating	0 P4SR	0.6 P4SR	1.2 P4SR
Just right	21	10	6
Too warm	3	11	13
Much too warm	0	1	2
Hot	0	2	3

Table 24. Distribution of ratings under thermal load in the experimental group.

In comparing the temperature in the classroom and in the climate chamber, 19 out of 24 rated the chamber warmer at 0.6, and 22 out of 24 at 1.2 P4SR; in the reference climate, the figure was 14 out of 24. In both stress conditions, the number of subjects who changed their rating in this way was greater than could be expected by chance (0.6 P4SR: $p < 0.05$; 1.2 P4SR: $p < 0.01$). Consistent with these ratings were the subjects' reports about preferred clothing during the exposures. In the neutral climate, 9; at 0.6 P4SR, 19; and at 1.2 P4SR, 21 children reported that they

would not have been able to sit in the chamber normally dressed. Again, the number of subjects changing their report under thermal load was statistically significant ($p < 0.01$). Moreover, only three children preferred to be normally dressed, two at 0 and one at 1.2 P4SR.

When the subjects left the chamber after three hours of exposure, they estimated, on average, that they could have been exposed for a further 83 minutes in the reference climate (very close to the estimate of the control group, 85 minutes), 71 minutes at 0.6 P4SR, and 60 minutes at 1.2 P4SR. The difference between 0 and 1.2 P4SR was statistically significant ($p < 0.05$).

Most subjects—70% or more— did not think that they could study very well if any of the three exposure conditions prevailed in school. All subjects reported that they had just enough to do, except two who reported too little work to do at 0.6 P4SR.

Irrespective of the thermal stress, about half of the children rated the learning tasks highly appreciated, whereas only one or two preferred working with the numerical tasks. Partington's Pathways Test and APT received about the same number of votes from the rest of the subjects.

Performance changes as a function of subjective report

Table 25 gives the performance changes under heat load with respect to the subjects' thermal ratings of the climate conditions. As a tentative answer to Figure 6 Question 2, it was found that most subjects reporting 0.6 P4SR "just right" were able to improve their performance to the same extent as the performance was impaired for subjects reporting 0.6 P4SR "too warm, much too warm", or "hot". However, the only

Climate condition	27°C ET - 0.6 P4SR	29°C ET - 1.2 P4SR		
Subjective report	Just	Too	Just	Too
Task	right	warm	right	warm
Learning 1	6%	-17%	5%	-17%
Learning 2	5%	-28%	15%	-17%
Retention 1:1	25%	- 1%	- 5%	- 2%
Retention 1:2	25%	8%	-16%	-11%
Retention 2	2%	- 2%	- 9%	- 2%
Addition (Σ calc. items)	[*] -10%	- 8%	-17%	^o - 8%
Multiplication (")	[*] -15%	[*] -13%	- 7%	-14%
Addition (error perc.)	[*] 70% ==≠	-152%	45%	5%
Multiplication (")	- 1%	^o -86%	-42%	7%
APT: raw score	24%	- 6%	-20%	- 7%
APT: bonus score	14%	- 4%	- 3%	- 2%
Auditory Startle Response	<u>43.1 dB</u>	<u>44.2 dB</u>	<u>44.2 dB</u>	<u>45.9 dB</u>
Partington 1	45.0 dB 8%	47.5 dB -12%	45.0 dB - 7%	47.9 dB - 1%
Partington 2	19%	17%	3%	6%
CFF: descending series	1%	- 1%	- 3%	- 1%
CFF: ascending series	3%	- 1%	4%	+ 0%

Table 25. Performance chnges on the psychological tasks under heat load—in percentage of the average performance in the reference climate 24°C ET, OP4SR, except for Auditory Startle Response with data presented in accordance with the formula $\frac{\text{stress condition} - \text{reference}}{\text{reference}}$

subjects reporting the climate 'just right' or 'too warm, much too warm or hot' (^o denotes 0.1, ^{*} denotes 0.05 statistical significance in testing performance changes within each group; ==≠ denotes 0.05 statistical significance in testing performance changes between groups; all tests were two-tailed).

statistically significant difference between the two groups of subjects was found for Addition accuracy.

At 1.2 P4SR, all subjects were equally adversely affected, irrespective of their thermal rating of the ambient heat. Although some subjects still perceived this heat load "just right", they were unable to improve their performance, as was the case at 0.6 P4SR.

D-index and Q-factor analysis

The analyses performed so far to answer Figure 6 Questions 1-6 have conclusively shown that the environmental heat influenced the subject's mental and perceptual performance. Statistically significant adverse effects were found in the numerical tasks. A marked negative trend was noted in the Learning tasks too. At 0.6 P4SR, the improvement in performance in memory and cue-utilization tasks was significant, and the subjects' attention was changed, which means that auditory signals elicited a startle response at significantly lower sound pressure levels. An increase in both rectal temperature in particular and skill measured either as pre-exposure test performance or as performance in the neutral reference climate was predictive with respect to heat-induced performance changes. In general, intellectual ability or personality or thermal sensation was not associated with performance changes. Even if some significant results were obtained with respect to these variables, the results must be considered tentative in view of the number of comparisons made.

The analyses presented hitherto thus indicated whether the effects of heat stress on performance were influenced by physiological strain, skill, general intelligence, personality, and thermal sensation, separately. However, the analyses did not

indicate whether some of the adversely affected subjects were depicted by specific patterns formed by all or only some of these variables. Differences between adversely affected and unaffected subjects with respect to the interaction of these variables were not studied. Therefore individual differences among adversely affected and unaffected subjects were described and studied by means of D-index and Q-factor analysis (for definition of affected and unaffected subjects, see above, Experimental design and statistical analysis).

Distribution of D-index and criteria for item selection

When testing goodness of fit of the observed to the theoretical frequency distribution of D-index, it was found in all 44 analyses that the distributions differed more than could be expected by chance ($p < 0.001$). In both of the heat-stress conditions and also on all performance tasks, the observed frequency of discriminating items was far lower than was theoretically expected, and the observed frequency of low D-indices was correspondingly high. This indicated that with respect to the 220 studied item characteristics, the more performance affected subjects under heat load, on average, very closely resembled the less affected ones.

In view of the main results, referred to above, this conclusion might seem paradoxical. The similarity of the two groups of subjects can be explained in at least three ways.

a) The subjects voluntarily attending the study were not randomly sampled, but selected from two normal school classes in a specific city district. Therefore they were alike not only in such characteristics as age, schooling, and social and cultural experience, which were not investigated, but

probably also in intellectual ability, personality, and thermal experience.

b) The subjects were exposed to the same environmental temperatures, a standardized procedure being followed in order to obtain uniform exposure and test conditions. As shown in the analyses of variance, the subgroups in the experimental group were similar.

c) Factors such as intelligence, in particular, and to some extent also personality, were of minor importance as general predictors for thermally-induced performance changes. High scorers in the intelligence test and stabilized subjects did not consistently perform either better or worse than other subjects.

However, the homogeneity of the experimental group, with regard to the individual characteristics in the item list, does not indicate that the adversely affected and the unaffected subjects were alike in all respects. None the less, even seemingly unimportant characteristics such as intelligence could be very typical for a specific small group or factor of subjects. Furthermore, some subjects could be depicted by several intrinsically less significant characteristics, but which in combination were important with regard to the subjects' possibility of sustaining heat load.

On the basis of a careful inspection of the frequency distributions to study in which respects performance affected and unaffected subjects differed, it was considered the best strategy to settle $D \geq 0.167$ as an arbitrary cut-off limit and discard items with lower D-index at item selection for the Q-factor analyses. In general, more than 100 items could thus be selected. In this way, the opposed requirements of retaining a sufficient number of items to make the Q-factor analyses meaningful, on the one hand, and

still have items with discriminatory power, on the other, were met. In some cases, the cut-off limit had to be slightly lowered (0.133 and 0.100) to get enough items.

Q-analysis

In accordance with the results of Kaiser (Harman 1967, p. 198), from six to nine of 24 possible factors could be extracted in the Q-factor analyses, and these factors explained about 70% of the total variance. Mostly, 20 children or more, i.e. more than 80% of the subjects, were incorporated in the obtained factor solutions, when factor loadings of 0.50 or higher were used as an arbitrary criterion of factor belongingness. The cut-off limit of the D(w)-index at factor identification was fixed at 0.50.

Learning

The best descriptive factor solution with respect to the two Learning tasks was obtained for Learning 2 at 0.6 P4SR (see Appendix Table 16). Of the 14 subjects whose Learning performance was impaired, four were found to be a) verbally less intelligent, and concerning personality characteristics, were b) inattentive, rigid, tense, and anxious (Factor 1). Another four subjects were characterized by high absolute measures of a) rectal, skin, and mean body temperature; and b) high pulse rate; but c) low gross sweat rate, g/h; resulting in d) high deviation measures of skin and mean body temperature; and e) low deviation measure of sweat rate, $\text{g/m}^2/3\text{h}$ (Factor 4).

Concerning the Factor 4 Group it seems reasonable to suggest that the evaporative cooling effect was

probably insufficient to counteract the disturbance of the heat balance, as reflected by the raised body temperature. Moreover, it is to be noted that these subjects were also exposed to 0.6 P4SR at their first trial (cf. the interaction pattern in Figure 10).

Five of the 10 subjects who improved their performance under heat load had comparatively a) low and unchanged body temperatures (Factors 2 and 3). In addition, some of them were b) stabilizers (Factor 3), whereas the rest could not be altogether accurately described with respect to personality factors, although cumulative signs were found (Factor 2). The other five subjects most of whom improved their performance, were characterized by either a cumulative personality classification, indicating obsession (Factor 5), or by a high intelligence (Factor 6).

In the factor solution for Learning 1 at 0.6 P4SR, two factors from Learning 2 reappeared to some extent. Factor 1 of the two solutions—accounting for 21% of the total variance—contained exactly the same performance-deteriorated and physiologically-affected subjects. Belonging to Factor 2 of Learning 1—in all containing four subjects—were those three intelligent subjects that had the highest factor loadings in Factor 6 of Learning 2.

Thus it appeared that general intelligence, and especially verbal ability for some subjects, determined direction and degree of performance change under heat stress. The analyses showed that some, but not all, of the less intelligent subjects were adversely affected, whereas some, but not all, of the high intelligence scorers were able to improve their Learning performance.

Although the factor solutions with respect to the two Learning tasks at 1.2 P4SR were less unequivocal, many

of the performance-deteriorated subjects were characterized in about the same way as they were at 0.6 P4SR, i.e. signs of disturbed heat balance in connection with low intelligence and exposure to the stress condition, 1.2 P4SR, at the first trial. The opposite qualities were attributed to most of the less affected subjects, some of whom improved their performance.

Memory

When the subjects were ranked and depicted with respect to performance change on the memory tasks, the best factor solution was noted for Retention 2 at 0.6 P4SR (see Appendix Table 17). This factor solution was almost a complete replication of the factor solution for Learning 2 in the same condition; consequently, the items descriptive of the factors were almost identical, too.

Regarding the rest of the memory measurements, the factor solutions were ambiguous, as some factors included both subjects with marked performance deterioration and subjects with unchanged or improved performance. About half of the extracted factors grouped the subjects in a meaningful way, i.e. discriminated between affected and unaffected subjects. In three of the five analyses, a tentative factor appeared that characterized subjects with impaired performance as low gifted in combination with signs of inattention and a dissociative adaptation pattern in CWT.

Arithmetic

Although less distinct factor solutions were obtained for the two numerical tasks, some factors were of

interest from an explorative standpoint.

About half of the less affected subjects at 0.6 P4SR—with a change of Multiplication speed less than the median change—were characterized by a) low intelligence and b) low pre-exposure test performance (Factors 1 and 2). This was consistent with previous findings. Moreover, the subjects belonging to Factor 1 reported that they c) could not withstand any further heat exposure. The subjects belonging to Factor 2 and c) exposed to 0.6 P4SR at their first trial had d) increased skin temperature and pulse rate, and concerning personality characteristics, showed signs of e) rigidity and instability (CD_k).

Only one factor was unambiguously made up of four performance deteriorated subjects characterized by a) weak or moderate physiological reactions, b) high pre-exposure test performance, c) stabilized cognitive control, and d) an initial exposure to the reference climate.

Subjects with adversely affected speed of Multiplication at 1.2 P4SR either had high pre-exposure test performance or maintained physiological functioning when exposed to 1.2 P4SR at the second trial.

Some of the less affected subjects at 1.2 P4SR were classified C_k or CD_k , but in contrast to the results of the 0.6 P4SR analysis, they scored high in the intelligence test and in the pre-exposure test.

Gestalt perception—APT

The Q-factor analyses of the APT performance, in particular at 0.6 P4SR, very clearly showed that five of the 11 adversely affected subjects were

characterized by a) increased body temperature and b) pulse rate, probably owing to inability to regulate the heat balance by sweating (Factor 1; see Appendix Table 18). Another four with impaired performance were characterized by a) cumulative and dissociative signs in CWT, i.e. signs of rigidity and distractibility, in connection with b) low performance in the WIT II subtests Arithmetic and Object assembly (Factor 3).

Almost all those who were able to maintain or improve their performance were also able to a) maintain the heat balance, as indicated by low absolute and deviation measures of body temperature (Factors 2, 5, 6). Provided the heat balance was not upset, indications of relatively b) low intelligence did not seem to prevent the subjects from improving their performance under heat load (Factors 2, 5).

The analysis with regard to performance change in the warmest climate confirmed the findings of the 0.6 P4SR analysis, although the factor solutions were less unambiguous.

Auditory Startle Response

A study of the interaction of individual variables related to heat-induced changes of the startle response signal by means of D-index and Q-factor analyses was inadequate. A restricted range of the sound pressure level of the startle response eliciting signal caused a great number of ties when the subjects were ranked in this respect.

Cue-utilization—Partington's Pathways Test

Ten out of 13 subjects, whose performance in

Partington 1 was impaired at 1.2 P4SR, were characterized by a) increased physiological strain and showed signs of disturbed heat balance (Factors 1, 3, 8; see Appendix Table 19).

This was valid for about half of the performance-impaired subjects in the middle climate too; no subject in the other deteriorated half was characterized by maintained heat balance. Moreover, this finding could to some extent be traced in the two factor solutions with regard to Partington 2.

Other items characterizing most of the adversely affected subjects at 1.2 P4SR were b) high residual variability in CWT (V-values) indicating inattention and distractibility (Factors 1, 8), although this characteristic did not seem to be crucial (Factor 3, and analyses not shown). Finally some of the adversely affected subjects also had a c) low WIT II score (Factor 8, and analyses not shown) or an initial exposure to 1.2 P4SR (Factor 3), but neither of these characteristics was crucial (Factor 1).

The less performance-affected subjects were described in the opposite way. In the four factor solutions in the Partington tests, almost every factor that contained subjects with maintained performance under heat load was depicted by a) moderate or small physiological deviations from the reference values of the neutral climate (Factors 4, 5, 6). Another frequent characteristic was b) unvaried or increasing reading times in CWT, indicating stabilized or cumulative primary or secondary personality classification of the less affected subjects, especially concerning the performance change in Partington 1 (Factors 4, 6, and analyses not shown).

To summarize: The most marked differences between adversely affected and unaffected subjects were noted

with respect to heat balance and personality characteristics.

DISCUSSION OF PSYCHOLOGICAL DATA

The relation between previous and present findings

The statistically significant results obtained with respect to speed of work in the two numerical tasks, attention in the Auditory Startle Response test, and cue-utilization in Partington 2 were consistent with the introductory interpretation of results obtained in previous heat stress studies (see Figures 1-5, and Tables 1-8). According to these conclusions, based on the literature review, a linear trend is to be expected for mental tasks, whereas a curvilinear trend is to be expected for perceptual and non-motor tasks performed under heat load. Also the tentative findings in the two Learning tasks were consistent with the empirically derived conclusions.

The imposed heat stress affected the subjects' mental and perceptual performance in most tasks, in accordance with the outlined theoretical model. The results in the two numerical tasks confirmed, with statistical confidence, the prediction that the number of items attempted would be reduced at 0.6 and 1.2 P4SR, corresponding to 27° and 29°C ET, respectively. The hypothesis about a curvilinear trend concerning changes in attention and cue-utilization (Partington 2) was also verified by the results, and an optimum performane was achieved at 0.6 P4SR.

Differences between practised and not practised tasks

It is interesting that, for all the tasks with statistically significant results in accordance with

the empirically derived conclusions and the theoretical predictions, no learning effects from trial to trial were noted in the control group. In contrast to these tasks, the main effects of temperature were not statistically significant for those tasks in which reliable learning effects appeared in the control group, i.e. Learning, APT, and Partington 1.

However, in the two Learning tasks, the APT, and the Partington 1, statistically significant interaction and simple main effects were found between the climate conditions and their order of presentation. Concerning Partington 1, the interaction effect obviously reflected only a learning effect that was not in any way influenced by the heat, as it was not linked to climate sequences beginning or ending with a specific ambient temperature (see Figure 14; Appendix Table 14). On the other hand, tests of simple main effects in the two Learning tasks and in the APT indicated that statistically significant performance decrements under heat load were found only for subjects who, at their first trial, were exposed to 0.6 P4SR (Figures 10, 13; Appendix Tables 5, 6, 12, 13).

These results suggest two things:

a) They indicate that the effects of a moderate heat stress at 0.6 P4SR or 27°C ET—a climate assumed to be dearousing for most subjects—can be more detrimental for paired-associate learning and perceptual organization than a physiologically more heavy heat stress at 1.2 P4SR. According to the heat-stress-arousal model, this condition was supposed to be arousing.

b) The absence of main effects of heat for the two Learning tasks and the APT, but the presence of interaction effects, indicated that small general effects of heat were probably masked and confounded

by specific heat-induced learning-how-to-learn effects. In particular, this seemed valid for the two Learning tasks for which a not statistically significant performance deterioration averaging a consistent 10% was found when the subjects were heat loaded.

The analyses of simple mean differences showed that these specific effects acted most strongly when the subjects initially tried to acquire an efficient way of handling the task. The effects did not appear at the second or third trial after the subjects had been acquainted with the task at the first trial. Concerning the two Learning tasks, an attempt was made to adjust the performance score for carry-over effects estimated by means of the results of the control group and using intelligence data for covariate adjustment. This attempt was not successful probably because intelligence accounted for only about 30% of the total variation in Learning performance.

In the practised and routinely executed numerical tasks, the main effects of heat were not accompanied by any interaction effects. Nor did any interaction effects appear in Partington 2, which measured cue-utilization and attention and was not characterized by learning effects in the control group.

To summarize: The findings for practised and not practised tasks indicated that general effects of heat stress are probably most easily detected by practised tasks. Because main effects of environmental warmth are not confounded with learning-how-to-learn effects for practised tasks, they seem to be preferable to not practised tasks. This conclusion agrees with the prevalent usage of experimental methodology in the field of heat-stress research.

However, not practised tasks can be equivalent to practised tasks, provided that learning neutralized heat-induced effects in not practised tasks are analysed with respect to heat strain parameters, instead of heat stress parameters. This is discussed in detail below.

Moreover, the choice of performance tasks ought to be determined by the situation that is to be evaluated. When the school situation is studied, the effects of heat in not practised mental tasks are of great concern. On the other hand a study of practised motor tasks would be more relevant if effects of heat on routine industrial or office work are investigated.

Differences in trend between Learning and Retention measurements

The results of the measurements of Retention did not confirm the hypothesis of a linear trend with optimum performance in the neutral climate. Instead, a curvilinear trend was noted at the first two measurements of Retention; this means that an optimum performance was achieved at 0.6 P4SR, as was the case for the Auditory Startle Response test and Partington 2. The different trends appearing for the Learning and Retention measures, and the fact that the heat-induced changes in Learning and Retention did not correlate and that changes of Learning were dependent on changes in rectal temperature, whereas changes in Retention were not, suggest that the processes of acquiring or learning paired-associates and the recall processes were differently affected by the heat.

The difference could be due to the subjects having been heat exposed for a longer time when the measurements of Retention were made. According to the

hypothesis of progressively increasing thermal fatigue effects proposed by Wing (1965), the subjects would thus have been more adversely affected at the measurements of Retention during the second or third hour of exposure than at the measurement of Learning during the first hour. However, no progressively increasing heat-induced effects on performance appeared either from Learning 1 to Learning 2 or from Retention 1:1 to Retention 1:2. Therefore Wing's hypothesis cannot explain the different trends for Learning and Retention.

An alternative explanation could be that the processes of learning differ in nature and dynamic from the recall processes. This possibility seems reasonable with respect to the absence of any relation between the heat-induced changes of Learning and Retention performance. Defining arousal by means of affectively toned paired-associates and explaining consolidation of them in terms of the function of reverberating neural circuits, Kleinsmith & Kaplan (1963) suggested and also demonstrated a mutual interaction of arousal, learning, and time of recall. However, their results indicated poor immediate recall (2 min) under high arousal learning in combination with strong long-term retention (>45 min). Low arousal effects were in the opposite direction. This interaction pattern is discordant with the results of this study obtained under psychophysiologically-induced arousal. Thus the curvilinear retention trend cannot be adequately explained in terms of the hypothesis of Kleinsmith & Kaplan. Beh & Hawkins (1973), studying the relation between arousal and retention of verbal material, concluded that the effects of arousal during training on learning efficiency, retention, and later recall are not at present clearly determined.

In view of the obtained curvilinear trend in the tasks measuring attention and cue-utilization, it seems that

the heat-induced changes of Retention were more associated with attentional phenomena than the Learning processes. Researchers within the field of memory also emphasize that memory processes cannot be studied isolated from perceptual and attentional processes (Broadbent 1957, 1958, Norman 1969). Consequently, as a third explanation of the curvilinear trend, it could be supposed that, when the level of arousal was decreased at 0.6 P4SR, the number of memory cues utilized increased correspondingly as did the perceptual cues when the attentional field was extended. But the absence of any correlation between Partington 2 or the Auditory Startle Response test, on one hand, and Retention 1:2, on the other, does not support this idea.

However, the curvilinear trend with an improvement in Retention at 0.6 P4SR can be explained in terms of the retroaction hypothesis. This hypothesis presumes that forgetting a learnt material depends on the interfering effects of intervening events.

It seems reasonable to suggest that the interfering effects of the performance tasks administered between Learning 1 and Retention 1:1 and 1:2, respectively, were less marked at 0.6 P4SR—a condition supposed to be dearousing—than they were at 0 or 1.2 P4SR. The decreased interference at 0.6 P4SR resulted in an improved retention score. The nonexistent improvement for Retention 2 could be due to this measurement being made only 15 minutes after Learning 2, and during that time, only two tasks being given (see Table 12). Any heat-induced interference effect for Retention 2 would therefore be less than for Retention 1:1 and 1:2.

Differences between Partington 1 and 2

In accordance with prediction, the favourable effect of a decreased level of arousal at 0.6 P4SR on cue-utilization was most marked in the difficult Partington 2, whereas, surprisingly, no heat-induced performance changes appeared in Partington 1. Besides the absence of a curvilinear trend, a number of other facts indicated that Partington 1 was probably lacking construct validity and did not measure cue-utilization and attention in the same way as Partington 2.

Tasks measuring attention could be expected to have low re-test correlation, as attention is not a constant characteristic of the individual, but varies with the prevailing situational conditions. Partington 2 and the Auditory Startle Response test actually had low coefficients of correlation, whereas Partington 1 had not.

Another fact is connected with Easterbrook's (1959) suggestion that "the range of cue utilization can be regarded as an index of cerebral competence." Consequently attentional tasks should correlate with general intelligence. Partington 2 did so; Partington 1 did not.

In view of these facts, the absence of the expected inverted U-shaped curve for Partington 1 does not invalidate the outlined heat-stress-arousal model otherwise confirmed by the results in the two numerical tasks, the Partington 2 and the Auditory Startle Response test.

Performance tasks unaffected by the heat stress

The performance in the Gestalt Perception task, APT, and the CFF were only slightly influenced by the

thermal load. Concerning the APT—presumed to measure perceptual organization and storage processes—the absence of reliable heat stress-induced effects has previously been explained in terms of a confounding of thermal and learning effects.

However, it is also conceivable that concerning APT and CFF, both being more complex performance tasks, different processes were affected not only in different degrees, but also in different directions. Thus an adverse effect on one of these component processes, for instance perceptual organization, could be counteracted by another component process, for instance, recall or decision taking.

Because the most reliable results due to the heat stress were obtained in the routinely executed numerical tasks and in the attentional tasks, it seems as though comparatively simple performance tasks are preferable to more complex mental and perceptual tasks, as also previously suggested. However, the nonexistent effects of heat might also be explained by the fact that the so far discussed results were derived from analysis of performance with reference to ambient temperatures instead of physiological body temperatures.

The relation between physiological strain and performance change

The analysis of performance changes a function of physiological strain definitely showed that, for those tasks in which no reliable main effects of the ambient temperature appeared, there was a strong relation between, in particular, change in rectal temperature, but also change in pulse rate, on one hand, and change of performance, on the other (see Table 18).

As Table 19 shows, reliable performance decrements in the two Learning tasks, Partington 1 and APT, for the physiologically most affected subjects were counteracted by performance improvements for the less physiologically affected or unaffected subjects. These findings might explain the absence of any main effects of heat in these tasks in analyses where performance changes were associated with the prevailing heat stress, instead of the induced physiological strain.

The divergent findings for the physiologically affected and unaffected subjects can probably be explained in terms of the learning trends appearing in the control group in the four above-mentioned tasks. The tasks were new to the subjects, and they had to acquire an efficient technique of handling them. Apparently, this learning process was very sensitive to heat-induced changes in the thermoregulatory system, as a performance decrement under heat load was found only for subjects who were physiologically affected.

Possibly, the changes occurring in the thermoregulatory system had a secondary effect on the general function of the CNS. In terms of the neurophysiological theory of Hebb (1958), this secondary effect probably disturbed the consolidation of reverberating neural circuits. For subjects under physiological strain, the learning-how-to-learn the task was adversely affected; a phenomenon reflected by impairment of performance. Physiologically less affected subjects, on the other hand, could achieve an adequate technique of performing the task. Reverberating neural circuits were consolidated and formed phase sequences. Thus the physiologically less affected subjects improved their performance.

The obtained results indicate the importance of

analysing even not statistically significant main results with respect to physiological strain, instead of ambient heat stress. It seems reasonable to suggest that also in some of the reviewed studies which reported no reliable effects of heat stress on performance, adverse effects for subjects under physiological strain were neutralized by learning effects of some kind for physiologically unaffected subjects.

The data in Table 18 confirmed the prediction that deviation scores more accurately describe the effects of heat on performance and physiological function than absolute scores. The table also shows that the rectal temperature—a controlled physiological variable—was more closely associated with performance changes than the compensatory activity of sweating, or the secondary effect thereof reflected by the pulse rate. For most tasks, where the main effects of the environmental heat stress was neutralized by about 20-55% of the total variance in performance in fact depended on changes in rectal temperature.

Although the association between change of performance and gross sweat rate, g/h, was less marked than for the other measures of strain—probably owing to the low reliability of the measure of gross sweat rate—the fact that the relation to some extent appeared only at 0.6 and not at 1.2 P4SR agrees with the stress-strain reasoning.

At 1.2 P4SR, 13 of the 24 subjects exceeded the thermal equilibrium limit with respect to rectal temperature (38°C); this means that the evaporative cooling effect of sweating was no longer sufficient to keep the rectal temperature constant. The increased strain was reflected by the zero correlations at 1.2 P4SR, whereas at 0.6 P4SR, with only two subjects exceeding the thermal equilibrium limit, all the statistically

significant coefficients were positive, as expected. A high sweat rate at 0.6 P4SR counteracted an increase in body temperature and was slightly associated with a less adverse influence of performance.

In contrast to the strain induced performance changes in not practised tasks—the tasks that showed no reliable average effect of heat stress—the performance changes in practised or attentional tasks, with statistically significant stress induced main effects, were not associated with the degree of physiological strain. The performance in the two numerical tasks, or in the Auditory Startle Response test, or in Partington 2 did not correlate consistently with any of the physiological strain measures.

The nonexistent relation between rectal temperature and performance in practised tasks indicates that changes in performance can occur more or less independent of the function of the thermoregulatory system, at least as this is reflected by the rectal temperature. However, according to the outlined heat-stress-arousal model the performance changes would then depend on changes in arousal caused by afferent impulses from thermoreceptors in the skin.

To test this hypothesis, coefficients of correlation were calculated between absolute or deviation scores of skin temperature, on one hand, and performance change in the two numerical tasks, or in the Auditory Startle Response test, or in Partington 2, on the other. The results of this analysis did not confirm the hypothesis. However, the nonexistent relation between skin temperature and performance does not preclude the possibility that the performance changes were still associated with changes in arousal and activity of peripheral thermoreceptors, although these physiological and psychological changes were not associated with skin or rectal temperatures. Apparently,

the functional relation between performance impairment in these tasks and ambient temperature or physiological strain cannot be accurately explained by the presented results.

To summarize the discussion so far: It can be concluded that a causal relation seems to exist between increased physiological strain and performance deterioration provided

a) physiological strain is expressed by deviation in rectal temperature from base level, and

b) change of performance is measured by tasks that have not been practised before the subject is heat loaded.

When a task is learnt and can be routinely executed, the degree of physiological strain does not seem to be associated with the performance. The last conclusion agrees with the results obtained by Mackworth and other researchers who used practised tasks. However, they considered their results to be universal and did not notice the restricted applicability of the findings.

The divergent results obtained for practised and not practised tasks indicate that the functional relations among ambient heat stress, physiological strain, and performance are complex. There is no reason to alter the conclusion of Pepler (1963) "that it is a mistake to think of heat as having either a general or a specific effect on performance or indeed as having any single effect." This statement and the presented results indicate that it is important to appreciate the dynamic characteristics of heat stress and strain parameters and of performance tasks, instead of their structural attributes.

Statistical techniques for analysis of the relation
between physiological strain and performance

A word of warning must be directed against analysis of the relation between physiological strain and performance on the basis of mean absolute values. Such an analysis only shows how the two variables are, on average, affected separately by the heat; it does not indicate the functional relation between them.

If the environmental heat stress is raised and causes a reliable increase in the absolute mean level of physiological strain, whereas the absolute mean level of performance remains constant, it cannot be concluded that the two variables are independent. This is illustrated if the results in Tables 15, 16, and 17 are concurrently analysed, and the conclusion of this analysis is compared with the conclusion that can be drawn on the basis of the data in Tables 18 and 19.

Table 15 indicates that the rectal temperature during the third hour of exposure increased from 37.3°C at 0 P4SR to 37.6°C at 0.6 P4SR and to 38.0°C at 1.2 P4SR. At the same time, 24, 27, and 26 exposures were required to reach the criterion in Learning 2. As the absolute value of rectal temperature increased monotonically with each increase in heat stress, and the performance did not, a naive conclusion would be to state that rectal temperature and performance were not associated (cf. Pepler 1958).

However, the deviation data presented in Tables 18 and 19 definitely indicate a strong and reliable relation between change in physiological strain and change in performance ($r=.55$; statistically significant differences between physiologically affected and unaffected subjects both at 0.6 and 1.2 P4SR). What

can explain this paradox?

It probably depends on the fact that a comparison of average absolute values of rectal temperature and performance for a group of subjects will mask the true relation between the variables in the same way as group curves within the fields of psychophysics or learning can neutralize trends in individual curves.

Apart from this, correlation problems in general cannot be analysed appropriately by a study of the joint variation of two variables on three occasions. No one would draw any conclusion about the functional relation between rectal temperature and performance measured once for three subjects. However, firm conclusions about this relation have been presented on the basis of the joint variation of mean rectal temperature and mean performance in three climates (Mackworth 1950, Pepler 1958). That several subjects were studied in each climate does not justify the procedure.

Intra-exposure and inter-exposure consistency of performance changes

Irrespective of whether the relation between rectal temperature and performance was causal or non-causal, the changes of performance occurring under heat load were for most tasks characterized by high intra-trial and inter-trial consistency. The strength of intra-trial and inter-trial coefficients of correlation with respect to performance changes was approximately the same as previously found for the physiological strain variables (see Tables 15, 16, 17).

For the physiologically affected subjects, performance decrements averaging 50% were found in the Learning task during the first 30 minutes of exposure. These

adverse effects then remained constant to the last hour of exposure both at 0.6 and 1.2 P4SR. The same trend, although less marked, appeared for all subjects in the two numerical tasks.

The intra-trial findings indicated that the ambient temperature-duration hypothesis presented by Wing (1965) is probably not valid. The effects of heat on performance cannot be explained in terms of the exposure time and the ambient temperature. Time *per se* does not explain anything. The relevant aspects of time in this context are

- a) the content of time, and
- b) the functional processes occurring as time passes.

In heat-stress research, the thermoregulatory activity and the subject's psychophysiological and psychological reactions are system relevant functional processes.

Because the adverse effects on Learning for the physiologically affected subjects did not increase progressively under heat load, as the degree of physiological strain did, the introductory presented suggestion seems valid; initially activated compensatory and controlled mechanisms of the thermoregulatory system are crucial with respect to performance. When the subject later adapted to the heat stress and reached a thermal and psychological equilibrium, the performance also remained almost constant.

Moreover, it is to be noted that, with a rise in heat stress from 0.6 to 1.2 P4SR the physiological measures of strain increased significantly, while the performance decrements on all tasks, except the perceptual, changed very little (see Figure 9, Table 16). This finding supports the heat-stress-arousal model. Obviously, the de-arousing effects at

0.6 P4SR were as detrimental as the arousing effects at 1.2 P4SR.

The relation between skill and performance change

Besides the degree of physiological strain, skill was found to be an intervening variable associated with change of performance. In most tasks, the skilled subjects were consistently more adversely affected than the less skilled ones.

Concerning the performance tasks depicted in the control group by significant learning effects, it seems reasonable to suggest that the skilled subjects were more adversely affected because they were working almost at the limit of their ability. In fact, the skilled subjects had little room for improvement in the two Learning tasks and in the two versions of Partington's Pathways Test. In the thermally neutral reference climate, the pictures on the Learning tasks were, on average, re-exposed only once before the subjects had learnt them. In Partington 1, on average 21 of 24 circles and in Partington 2 all circles were correctly connected at 0 P4SR. The improvement of the skilled subjects at 0.6 P4SR was because they connected all circles in less than the stipulated 75 seconds.

If the skilled subjects could not improve their performance on account of restricted scope for improvement, the less skilled subjects could not become much worse in some tasks because there was a restricted scope for impairment. In the neutral climate, the less skilled subjects could correctly recall only about 12 and 8 out of 36 possible letters in Retention 1:1 and 1:2, respectively. Moreover, their mean raw score in the APT was 0.60 at 0 P4SR, which means that, on average, out of 9

designs less than 1 was correctly reconstructed.

Obviously, the variation in skill in some performance tasks was greater in the experimental group than in the pilot study group. The obtained divergent results for skilled and less skilled subjects indicate, as also pointed out by Poulton (1965), that for future heat stress research on not practised tasks, it is important to ensure that there is room for improvement for good subjects and room for impairment for poor subjects.

In the numerical tasks, seemingly contradictory results were obtained. Skilled subjects were more adversely affected by heat than less skilled ones in Multiplication, whereas the reverse was valid in Addition. However, these findings are not contradictory if they are analysed with respect to the dynamic instead of the structural characteristics of the tasks.

In Sweden, children learn to add and subtract during their first year at school, and learn multiplication during their third year. Thus, for the exposed children, Addition was probably a well practised and established skill. On the other hand, Multiplication was practised, but probably not completely mastered. The average error percentage in the control group was about 10% in Multiplication, but only 3% in Addition. It seems probable that those multiplying well when pretested had just learnt the technique of multiplying by heart at school, in contrast to poor pretested subjects who had not so thoroughly acquired the art. Under thermal stress, this new skill was easily affected, and the performance of the good subjects became worse, whereas it could not be much impaired for the poor ones.

Concerning Addition, the less skilled subjects were

probably working at full capacity in the reference climate and had no reserves to call on under heat load; thus their scores dropped. On the other hand, the skilled subjects could exploit their reserves; therefore their performance was less affected (see Tables 21, 22).

Intelligence , personality and performance change

The high intra-trial and inter-trial consistency found with respect to physiological and also performance changes indicate that the subjects' behaviour under heat load was very characteristic. None the less the data in Tables 20 and 23 show that the performance changes did not reliably depend on either general intelligence or personality characteristics, as was expected. Although minor differences existed between gifted and less gifted, and between cumulative and dissociative subjects, on one hand, and stabilized subjects, on the other, the different subgroups did not differ with statistical confidence. The intra-subgroup variation was so large that the performance changes for all subgroups on almost all tasks at both 0.6 and 1.2 P4SR were not statistically significant. Thus general intelligence and personality characteristics—as operationally defined in this study—cannot on average, explain or predict change of performance under heat load.

However, this conclusion does not exclude the possibility that specific interaction patterns between general intelligence and personality in combination with other individual characteristics might be associated with performance changes. This possibility was also tentatively indicated in the Q-factor analyses.

It also seems reasonable to suppose that intelligence and personality characteristics could be predictable and explicable factors in groups more heterogeneous than the investigated group.

Psychological strain and performance change

Compared with the effects of physiological strain, the effects of psychological strain—measured by thermal sensation—were small and showed such a variation that the changes of performance on almost all tasks could be attributed to chance factors. No effects associated with thermal sensation appeared at 1.2 P4SR, probably because they were masked by reliable effects of a marked physiological strain. However, at 0.6 P4SR, the effects on performance of physiological strain did not conceal the effects of psychological strain, as subjects rating this climate "just right" were consistently less adversely affected than subjects reporting 0.6 P4SR "too warm, much too warm", or "hot". This trend favours the suggestion that performance changes depend not only on the function of the thermoregulatory system but also on the subject's experience of the imposed heat and by his interpretation of the physiological strain reactions.

That thermal assessment was not associated with rectal temperature indicates that the subjects based their rating of the climate on their perception of the ambient heat stress and not on their perception of the body temperature, i.e. the heat strain. Unfortunately, the questionnaire given immediately after the heat exposure did not specifically ask how the subjects perceived the physiological heat strain. Such an introspective report would have provided information about the extent that a subject can discriminate between perception of external and internal heat, i.e.

between stress and strain. If a subject perceives the climate "too warm, much too warm," or "hot", he will not necessarily feel uncomfortably warm too. Thus psychological heat strain ought to be studied with respect to how the ambient temperature and the body temperature are perceived. The heat-induced psychological strain is probably greatest when the subject reports both himself and the climate "too warm, much too warm," or "hot".

Information given by multivariate analyses

The results of the Q-factor analyses indicated that the technique is applicable to experimental data. However, ambiguous factor solutions based on a total of some 220 items (these analyses have not previously been referred to) and the outcome of the D-index analyses showed that a prerequisite for the Q-methodology to be efficiently descriptive of experimental item characteristics of affected and unaffected subjects is that item characteristics lacking discriminatory power are discarded by means of D-index analysis previous to the Q-factor analysis. Selection of discriminatory items can, of course, be based on some technique other than D-index analysis. Item selection can also be made with reference to theoretical predictions, but this strategy must be considered less well suited for exploratory purposes (cf. Problem analysis, and Experimental design and statistical analysis; see Figure 6).

The clearest factor solutions were obtained at the moderate heat of 0.6 P4SR for those tasks that were not practised and, in the control group, were characterized by significant learning effects from trial to trial, i.e. Learning, APT, and Partington 1. For these tasks, the factor solutions indicated that adversely affected subjects definitely differed from

unaffected subjects with respect to the structure of item characteristics. As Appendix Tables 16-19 showed, none of the adversely affected subjects belonged to factors composed of unaffected subjects and *vice versa*. Thus, by means of the D-index and Q-factor analyses, it was possible to discriminate between subjects improving and impairing their performance on the basis of how they differed with respect to combinations of individual characteristics such as physiological strain, intelligence, personality, and skill.

Concerning practised tasks such as Addition and Multiplication—depicted by reliable main effects of heat stress—the factor solutions were mostly less distinct and informative. Some of the extracted factors were composed of both much and also less adversely affected subjects. In contrast to the not practised tasks, almost any subject was able to improve his performance on the numerical tasks.

However, ~~even~~ such ambiguous factor solutions as were noted with respect to the numerical tasks and some other tasks at 1.2 P4SR conveyed some information. They indicated that the performance changes were general and not restricted to specific subgroups of subjects. Although the analysis of variance showed that none of the intervening variables illustrated in Figure 6 *a per se* were associated with heat-induced performance changes, the analysis of variance findings did not indicate that combinations of the intervening variables were unassociated with change of performance. However, this was indicated by the Q-factor analysis.

The unequivocal grouping in the not practised tasks of the subjects in six to nine factors indicated that the Q-factor analysis, in addition to discriminating between adversely affected and unaffected subjects, distinguished between subgroups of individuals with

respect to their item structure. The answers to Research Questions 7-9 thus supplemented the answers to Questions 2-6.

Concerning, for instance, Learning 2 and Retention 2, the answers to Questions 2-6 indicated that performance changes were not, on average, associated with either general intelligence or personality *per se*. However, the answers to Questions 8-9 showed that at least some of the performance impaired subjects were both less verbally intelligent and inattentive, rigid, tense, and anxious. The Q-factor analyses also indicated that some of the subjects, who were able to improve their performance, besides being characterized by low physiological strain—as was known from the analysis of variance findings—were also characterized by stabilized or cumulative CWT-patterns. The same type of additional information was revealed by the Q-factor analyses of the subjects with regard to performance in APT and Partington 1.

Thus the best descriptive Q-factor analyses accomplished what was intended. They showed that, provided the effects of heat on performance were not general and very marked, i.e. all subjects were not almost equally affected as was the case in the two numerical tasks, the experimental effects could be explained in terms of interaction between intrinsically not significant individual characteristics such as intelligence or personality. It would have been impossible to reach such a conclusion if the data had been subjected to only analysis of variance. As previously mentioned, the aim of future research will be to cross-validate the exploratory findings of the Q-factor analyses performed in this study.

Generality of results

As already pointed out, the statistically significant results were consistent with the interpretation of findings in the reviewed heat stress studies. Thus a linear trend is to be expected for mental tasks, whereas a curvilinear trend is to be expected for perceptual and non-motor tasks. However, although this conclusion can possibly be generalized to other conditions, some restrictions concerning the generality of the results must be exphasized.

First, the results were obtained in a well-controlled laboratory study. The children were exposed alone and were dressed in shorts during the exposure. They had to perform a number of mental and perceptual but non-motor tasks according to a standardized procedure. Obviously, discordant findings can be expected in ordinary school conditions, where normally dressed children work in groups with tasks measuring aspects of performance other than those studied in the climate chamber.

Whereas a statistically significant impairment in both Multiplication and Addition was found in this study, Holmberg & Wyon (1969), in a field study on a comparable sample, did not report any influence on arithmetical work. The heat load was slightly lower in their study than in this, which would explain the discordant findings. But it seems reasonable to suppose that those findings were also, to some extent, due to the evaporative cooling effect of sweating, which for normally dressed subjects differs from that of subjects dressed in shorts. Moreover, when subjects are heat exposed in groups, the arousal effects of the social setting will add to the arousal effects of the climate.

Secondly, the subjects were ten-year-old school

children. Their thermoregulation differs from the thermoregulation of adults (Löfstedt 1966). The sweat rate and the heat tolerance are lower than those of subjects between 20 and 40 years of age. Thus discrepant findings can be expected for subjects in the 20-40 age interval and even for older subjects, as their thermoregulation differs from that of the other two groups.

However, although the ambient temperature which influences thermoregulation and performance might differ for various age groups, it cannot be expected that the direction of the observed relation between physiological strain and performance differs. Possibly the strength of the relation can change slightly, but in view of the findings of Wilkinson *et al.* (1964), Colquhoun & Goldman (1972), and Trygg (1972), the conclusion that physiologically affected subjects are most easily performance affected under heat load must be considered general.

Thirdly, the experimental group was homogeneous in intelligence and personality factors. Therefore the conclusion that heat-induced performance changes are not related to these factors cannot be generalized to heterogeneous groups, which show a considerable dispersion of intelligence and personality characteristics. Furthermore, intelligence and personality factors measured by other tests might be associated with performance changes in heat.

C O N C L U S I O N S

Based on the results obtained in this experimental study and the discussion of the findings, the following conclusions are drawn.

1. An indoor climate of 0.6 or 1.2 P4SR corresponding to 27° and 29°C ET, respectively, for naked subjects should be avoided in school buildings because the thermal load of these climates gave rise to significant increases in physiological and psychological strain, and mental performance was adversely affected.

An increased sweat rate at 0.6 P4SR can make the clothing damp and insalubrious and could give rise to bad odour. At 1.2 P4SR, the thermal equilibrium limit might be exceeded, and can be regarded as the maximum tolerable for prolonged heat exposure. Most subjects also perceived 1.2 P4SR as "too warm, much too warm," or "hot".

2. The effects of heat load on the thermoregulatory system and on performance were displayed after a short period of exposure. They reached almost full strength during the first hour of exposure. Small progressively increasing effects were noted with respect to rectal temperature and gross sweat rate, whereas no such effects were found with respect to pulse rate and performance.

These facts do not support the hypothesis that changes in performance are associated with thermal fatigue. A more plausible explanation seems to be that performance changes under heat load are dependent on a functional reorganization of the thermoregulatory system. This autonomous reorganization probably influences the functioning of the CNS.

3. The rectal temperature was found to be the most

consistent and reliable measure of physiological strain, whereas sweating less accurately indicated changes in physiological strain. However, the degree of physiological strain under heat load could not be predicted for rectal temperature from knowledge of the resting base level at O P4SR.

4. In practised tasks such as Addition and Multiplication, reliable main effects of heat appeared to indicate that the performance was reduced by about 10%. These effects occurred independent of the degree of physiological and psychological strain, general intelligence, and personliaty, both separately and in combination.

The findings indicated that there was no direct causal relation between rectal temperature below 38°C and change of performance in practised tasks. The nature of the mechanism causing heat-induced impairment in such tasks is not clear, although the results were in accordance with the heat-stress-arousal model outlined.

5. An inverted U-shaped relation between heat load and attention was found for all subjects and was not associated with individual characteristics. This quadratic trend, indicating that an optimum cue-utilization was achieved at moderate heat load and physiological strain, supported the suggested theoretical model. However, as level of arousal was not measured electrophysiologically, no conclusive evidence was found in support of the model.

6. The performance changes in not practised tasks were strongly associated with the degree of physiological strain and in particular with the heat-induced deviation in rectal temperature from its base level at O P4SR. Performance changes were less predictable with physiological strain expressed by means of

absolute measures instead of deviation measures.

Thus, in contrast to practised tasks, a causal relation seems to exist between deviation in rectal temperature and performance in not practised tasks. Such tasks have to be learnt before the subject can perform them efficiently. This learning-how-to-learn process is sensitive to an increase in physiological strain. It must be emphasized that, if learning-how-to-learn effects are operating, adverse effects for subjects under physiological strain could be neutralized by learning effects for physiologically unaffected subjects.

7. In addition to physiological strain, skill was consistently associated with heat-induced changes of performance. Subjects working at the limit of their ability, because they had recently acquired, but not completely mastered, the technique of performing a new task, were most adversely affected by heat.

8. Parametric and non-parametric analyses of variance indicated that the effects of heat load on performance were independent of thermal sensation and of individual characteristics such as general intelligence and personality analysed separately. However, Q-factor analyses made clear that some combinations of these factors can be characteristic for adversely affected subjects.

9. The fact that thermal assessments of the climate were not associated with rectal temperature indicated that heat stress might be rated without confounding with heat strain. It also indicated that thermal assessment of the environmental warmth would not be used as a measure of heat-induced psychological strain. Such a measure would, instead, be based on assessment of both heat stress and physiological strain.

S U M M A R Y

A review of heat-stress studies suggested that mental, perceptual, and psycho-motor tasks have mainly been studied in laboratory experiments performed on heat acclimatized fit young men. The subjects were usually given extensive practice on the performance tasks, which thus were well learnt prior to heat load. The exposure time has varied from less than one hour to several hours. The emphasis recently shifted from an exploration of the relation between constant ambient temperature and performance to studies of performance changes under controlled hyperthermia or as a function of ambient temperature swings.

The reviewed studies indicated that an ambient temperature exceeding 30°C ET will probably impair the performance on mental, perceptual, and psycho-motor tasks for subjects stripped to the waist. A critical zone exists between 27° and 30°C ET. No general relation between ambient temperature and performance change has been found. However, in most studies of mental tasks, the relation was linear, whereas for perceptual but non-motor tasks, it was curvilinear and optimum performance was achieved at $24\text{--}27^{\circ}\text{C}$ ET.

Previous studies often reported no causal relation between body temperature and performance, whereas recent studies of performance under controlled hyperthermia have shown that adverse performance changes under heat load occur when the body temperature exceeds 38°C . For sedentary work, a constant indoor climate seems preferable to ambient temperature swings.

Even if high degree of motivation increases the performance under heat load, it has been shown that the adverse effects of heat stress on performance are not counteracted. Moreover, subjects working

at optimum effort and those working at the limit of their ability were found to be most easily adversely influenced by environmental warmth.

A psycho-physiological model was proposed suggesting that under heat load the level of arousal is a function of both central and peripheral neural factors. Dearousing effects will probably appear when the organic temperature is slightly increased above the ordinary base level. A further increase of the organic temperature will be arousing. According to this model, most tasks, except cue-utilization and similar perceptual and non-motor tasks, will be impaired under moderate heat load owing to underarousal, and under heavy heat load owing to overarousal. Perceptual tasks measuring cue-utilization and attention will display an inverted U-shaped trend, whereas for signal detection tasks, a direct U-shaped trend is predicted.

Heat-induced physiological and psychological strain and its relation to mental and perceptual performance was investigated in an experimental study. For three hours, on each of three occasions, an experimental group of 24 ten-year-old school children, dressed in shorts, were exposed to 30°, 36°, and 41°C DB in random order. As the air speed was 0.3 m/sec and the water-vapour pressure 15 mm Hg, the three climate conditions corresponded to 0, 0.6, and 1.2 P4SR or 24°, 27°, and 29°C ET. With the same procedure, a control group of 12 children were exposed to 0 P4SR. Before heat exposure, the subjects were tested for general intelligence, skill, and personality characteristics.

Rectal temperature, pulse rate, and sweat rate were all increased at 0.6 and 1.2 P4SR. At 1.2 P4SR, the thermal equilibrium limit, 38°C rectal temperature, was exceeded, and this climate was regarded as the

maximum tolerable for prolonged heat exposure. Most subjects also perceived 1.2 P4SR as "too warm, much too warm, or hot," but thermal ratings were not associated with body temperature.

The effects of heat load on the thermoregulatory system and on performance appeared after a short period of exposure. In practised numerical tasks statistically significant adverse effects of heat appeared averaging 10%. These effects occurred independent of physiological and psychological strain, general intelligence, and personality, both separately and combined.

A statistically significant inverted U-shaped relation between heat load on one hand, and cue-utilization or attention on the other, was found for all subjects independent of their individual characteristics.

No general effects of heat stress were found on not practised tasks, because adverse effects for physiologically affected subjects were neutralized by learning-how-to-learn effects for unaffected subjects. It was concluded that, for tasks to be learnt under heat load, there exists a causal relation between performance and increase in rectal temperature.

According to previous findings, skill was consistently associated with heat-induced performance changes. Although in most tasks, good subjects were more adversely affected than poor subjects, their performance was superior.

Generally, the effects of heat were not explainable in terms of either general intelligence or personality *per se*. However, for not practised tasks, some combinations of intrinsically unimportant individual characteristics were representative for adversely affected subjects.

A C K N O W L E D G E M E N T S

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Mrs B. Hommerberg patiently typed and retyped the manuscript and also typed the final version. Mr. J. Muhi drew the figures. Mr. F. Salisbury revised the English text carefully and instructively. Editor L. Walther prepared the manuscript for printing.

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A P P E N D I X

	Age, years		Height, cm		Weight, kg		Body area, m ²	
Experimental group (n=24)	10.9	± .4	143.0	± 7.1	36.2	± 7.5	1.20	± .14
Control group (n=12)	10.9	± .3	146.2	± 5.4	33.9	± 3.7	1.19	± .08

Appendix Table 1. Age, height, weight, and body area of subjects in the experimental and the control group—mean ± standard deviation.

Source	df	F
1 between subjects	pn-1	
2 climate sequences	p-1	2.43
3 subjects within sequences	p(n-1)	
4 subjects within sequence 1 (0 -1.2-0.6 P4SR)	n-1	C
5 subjects within sequence 2 (0.6-0 -1.2 P4SR)	n-1	
6 subjects within sequence 3 (1.2-0.6-0 P4SR)	n-1	
7 subjects within sequence 4 (0 -0.6-1.2 P4SR)	n-1	
8 subjects within sequence 5 (1.2-0 -0.6 P4SR)	n-1	
9 subjects within sequence 6 (0.6-1.2-0 P4SR)	n-1	
10 between sequences within 0 P4SR	p-1	10/13
11 between sequences within 0.6 P4SR	p-1	11/13
12 between sequences within 1.2 P4SR	p-1	12/13
13 within cells	pq(n-1)	
14 within subjects	np(q-1)	
15 climate conditions	q-1	15/27
16 between climates within sequence 1	q-1	16/27
17 between climates within sequence 2	q-1	17/27
18 between climates within sequence 3	q-1	18/27
19 between climates within sequence 4	q-1	19/27
20 between climates within sequence 5	q-1	20/27
21 between climates within sequence 6	q-1	21/27
22 linear trend	1	22/34
23 quadratic trend	1	23/35
24 sequence x climate condition	(p-1)(q-1)	24/27
25 difference in linear trend	p-1	25/34
26 difference in quadratic trend	p-1	26/35
27 climate condition x subjects within sequences	p(n-1)(q-1)	
28 climate x subjects within sequence 1	(n-1)(q-1)	C
29 climate x subjects within sequence 2	(n-1)(q-1)	
30 climate x subjects within sequence 3	(n-1)(q-1)	
31 climate x subjects within sequence 4	(n-1)(q-1)	
32 climate x subjects within sequence 5	(n-1)(q-1)	
33 climate x subjects within sequence 6	(n-1)(q-1)	
34 climate x subjects within sequences (linear)	p(n-1)	
35 climate x subjects within sequences (quadratic)	p(n-1)	
36 total	npq-1	

Appendix Table 2. Mixed linear model for analysis of variance of a factorial design with climate sequences and climate conditions confounded and treated as fixed effects (C denotes Cochran's C-test)

Mathematical model: $x_{ijm} = \mu + a_i + \pi_{m(i)} + \beta_j + a\beta_{ij} + \beta\pi_{jm(i)} + \epsilon_{o(ijm)}$

μ = grand mean of treatment

a_i = effect of treatment i, which is a constant for all subjects within treatment population i

β_j = effect of treatment j, which is a constant for all subjects within treatment population j

$\pi_{m(i)}$ = constant associated with person m, who is nested under level a_i

$a\beta_{ij}$ = effect that represents nonadditivity of effects a_i and β_j

$\beta\pi_{jm(i)}$ = effect that represents nonadditivity of effects β_j and $\pi_{m(i)}$

$\epsilon_{o(ijm)}$ = experimental error, which is independent of other ϵ 's and is normally distributed, $\mu_{\epsilon} = 0$ and σ_{ϵ} ; according to this model $\epsilon_{o(ijm)}$ cannot be estimated separately from $\beta\pi_{jm(i)}$.

Subjects depicted by:	Performance change under heat load	
Item characteristic	$< m_d$	$> m_d$
Yes (e.g. $\leq Q_3$ on WIT II)	p_1	p_2
No (e.g. $> Q_3$ on WIT II)	q_1	q_1

Appendix Table 3. Contingency table for calculation of D-index;
 $D = p_1 - p_2$

Subject		B	
		Yes	No
A	Yes	a	b
	No	c	d

Appendix Table 4. Contingency table for calculation of G-index
(a, b, c, and d are proportions of item characteristics);
 $G = 2(a + d) - 1$.

Source	SS	df	MS	F
1	16727.653	23		
2	2005.237	5	401.047	< 1
3	14722.416	18	817.912	
4	2034.000	3	678.000	
5	1659.583	3	553.194	
6	1051.667	3	350.556	
7	1692.917	3	564.306	C = 0.47
8	6873.333	3	2291.111	
9	1410.913	3	410.304	
10	1040.333	5	208.067	< 1
11	3494.333	5	698.867	1.83
12	3524.208	5	704.842	1.84
13	20674.750	54	382.866	
14	12123.334	48		
15	117.362	2	58.681	< 1
16	888.500	2	444.250	2.69 ^o (2.78)
17	322.167	2	161.084	< 1 (2.83)
18	693.500	2	346.750	2.10 (20.84 ^{**})
19	176.167	2	88.084	< 1 (3.11 ^o)
20	2071.167	2	1035.584	6.26 ^{**} (1.68)
21	2019.500	2	1009.750	6.11 ^{**} (8.73 [*])
22	117.188	1	117.188	< 1
23	0.174	1	0.174	< 1
24	6053.638	10	605.364	3.66 ^{**}
25	2519.938	5	503.988	2.74 ^o
26	3533.701	5	706.740	4.82 ^{**}
27	5952.334	36	165.343	
28	959.500	6	159.917	
29	341.167	6	56.861	
30	99.833	6	16.639	C = 0.62 ^{**}
31	169.833	6	28.306	
32	3688.167	6	614.695	
33	693.833	6	115.639	
34	3313.375	18	184.076	
35	2638.958	18	146.609	
36	28850.987	71		

Simple mean differences				Critical HSD-values
Climate sequence 6	1.2	0.6		HSD _{0.05;3,36} = 22.24
0 P4SR:26.00 ₃	3.25	29.00 ^{**}		HSD _{0.01;3,36} = 28.29
1.2 P4SR:29.25 ₂		25.75 [*]		
0.6 P4SR:55.00 ₁				

Appendix Table 5. Analysis of variance of Learning 1 and tests of simple mean differences between climates within climate sequence 6 (^odenotes 0.1, ^{*}denotes 0.05 and ^{**}denotes 0.01 statistical significance; F-ratios within brackets obtained by testing simple main effects against their respective specific error term, i.e. ¹⁶/₂₈, ¹⁷/₂₉, ¹⁸/₃₀, ¹⁹/₃₁, ²⁰/₃₂ and ²¹/₃₃; subscripts denote order of presentation).

Source	SS	df	MS	F
1	11103.207	23		
2	1957.958	5	391.592	< 1
3	9145.249	18	508.069	
4	3776.333	3	1258.778	
5	1159.000	3	386.333	
6	1410.000	3	157.667	
7	707.000	3	235.666	C = 0.41
8	7385.000	3	820.556	
9	568.251	3	189.417	
10	1145.500	5	229.100	1.01
11	2426.500	5	485.300	2.15 ^o
12	800.375	5	160.075	< 1
13	12203.244	54	225.986	
14	5580.662	48		
15	108.250	2	54.125	< 1
16	508.668	2	254.334	2.99 ^o
17	824.666	2	412.333	4.85*
18	313.166	2	156.583	1.84
19	24.000	2	12.000	< 1
20	270.166	2	135.083	1.59
21	582.000	2	291.000	3.43*
22	31.687	1	31.687	< 1
23	76.562	1	76.562	< 1
24	2424.416	10	241.442	2.84*
25	742.433	5	148.487	1.87
26	1671.938	5	334.388	3.69*
27	3057.997	36	84.944	
28	536.666	6	89.444	
29	1242.000	6	207.000	
30	275.500	6	45.917	C = 0.4061
31	88.000	6	14.667	
32	689.833	6	114.972	
33	226.000	6	37.667	
34	1426.380	18	79.243	
35	1631.700	18	90.650	
36	16683.869	71		

Simple mean differences

Climate sequence 2	0	0.6	Climate sequence 6	1.2	0.6
1.2 P4SR:20.00 ₃	2.00	18.50*	0 P4SR:26.75 ₃	4.50	16.50*
0 P4SR:22.00 ₂		16.50*	1.2 P4SR:31.25 ₂		12.00
0.6 P4SR:38.50 ₁			0.6 P4SR:43.25 ₁		

Critical HSD-values

HSD_{0.05; 3, 36} = 15.94

HSD_{0.01; 3, 36} = 20.28

Appendix Table 6. Analysis of variance of Learning 2 and tests of simple mean differences between climates within climate sequences 2 and 6 (^o denotes 0.1, * denotes 0.05 statistical significance; indices denote order of presentation).

Source	SS	df	MS	F
1	2427.986	23		
2	147.903	5	29.581	< 1
3	2280.083	18	126.671	
4	481.584	3	160.528	
5	568.665	3	189.555	
6	596.667	3	198.889	
7	131.043	3	43.861	C=0.26
8	356.667	3	118.889	
9	144.918	3	48.306	
10				
11				
12				
13				
14	1021.333	48		
15	66.194	2	33.097	1.36
16				
17				
18				
19				
20				
21				
22	3.251	1	3.251	< 1
23	62.674	1	62.674	2.36
24	80.472	10	8.047	< 1
25	32.604	5	6.521	< 1
26	47.866	5	9.573	< 1
27	874.666	36	24.296	
28	109.167	6	18.194	
29	61.833	6	10.306	
30	47.333	6	7.889	C=0.36
31	124.167	6	20.694	
32	214.833	6	35.806	
33	317.333	6	52.888	
34	396.375	18	22.021	
35	478.290	18	26.572	
36	3449.319	71		

Appendix Table 7. Analysis of variance of Retention 1:1.

Source	SS	df	MS	F
1	2413.778	23		
2	150.611	5	30.122	< 1
3	2263.167	18	125.732	
4	487.584	3	162.528	
5	664.668	3	221.556	
6	711.585	3	237.195	
7	88.668	3	29.556	C=0.31
8	259.332	3	86.444	
9	51.333	3	17.111	
10				
11				
12				
13				
14	1055.338	48		
15	188.361	2	94.181	5.70**
16				
17				
18				
19				
20				
21				
22	40.333	1	40.333	2.07
23	148.033	1	148.033	10.91**
24	272.639	10	27.264	1.65
25	168.667	5	33.733	1.73
26	103.967	5	20.793	1.53
27	594.333	36	16.509	
28	43.167	6	7.194	
29	51.333	6	8.556	
30	92.167	6	15.361	C=0.28
31	153.333	6	25.556	
32	88.167	6	14.694	
33	166.167	6	27.694	
34	350.000	18	19.444	
35	244.333	18	13.574	
36	3469.116	71		

Mean differences			Critical HSD-values
Climate	0	0.6	HSD _{0.05;3,36} =2.870
1.2 P4SR:12.96	1.83	3.96**	
0 P4SR:14.79		2.13	HSD _{0.01;3,36} =3.650
0.6 P4SR:16.92			

Appendix Table 8. Analysis of variance of Retention 1:2 and tests of mean differences between climates (** denotes 0.01 statistical significance).

Source	SS	df	MS	F
1	2764.209	23		
2	304.292	5	60.858	< 1
3	2459.917	18	136.662	
4	465.582	3	155.194	
5	748.000	3	249.333	
6	525.585	3	175.195	
7	311.583	3	103.861	C = 0.30
8	380.250	3	126.750	
9	28.917	3	9.639	
10	354.210	5	70.842	1.20
11	722.500	5	144.500	2.46*
12	212.335	5	42.467	< 1
13	3190.266	54	59.079	
14	1722.667	48		
15	7.583	2	3.792	< 1
16	201.500	2	100.750	4.97*
17	91.166	2	45.583	2.25
18	158.166	2	79.083	3.90*
19	177.166	2	88.583	4.37*
20	154.166	2	77.083	3.80*
21	210.166	2	105.083	5.18*
22	6.021	1	6.021	< 1
23	1.563	1	1.563	< 1
24	984.750	10	98.475	4.85***
25	357.599	5	71.520	6.31**
26	627.147	5	125.429	4.29**
27	730.333	36	20.287	
28	129.167	6	21.528	
29	243.500	6	40.583	
30	65.167	6	10.861	C = 0.33
31	120.167	6	20.028	
32	40.500	6	6.750	
33	131.833	6	21.972	
34	203.880	18	11.327	
35	526.490	18	29.249	
36	4486.876	71		

Simple mean differences

0.6 P4SR

Climate sequence	2	3	1	5	4
6:11.00	6.25	7.50	13.00* LSD	14.75* LSD	15.50* LSD
2:17.25		1.25	6.75	8.50	9.25
3:18.50			5.50	7.25	8.00
1:24.00				1.75	2.50
5:25.75					0.75
4:26.50					

Critical HSD'-value	Critical LSD'-value	Critical S'-values
HSD' = 16.19	LSD' = 10.95	S' = 11.60
0.05	0.05	0.05
		(1+4) - (2+6) + (3+5)
		S' = 13.39
		0.05
		(1+4) - (2+6)

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continued from above

Climate sequence 1			Climate sequence 3		
0	P4SR:14.00 ₁	4.25	1.2	P4SR:17.25 ₁	0.75
1.2	P4SR:18.25 ₂	5.75	0.6	P4SR:18.50 ₂	7.00
0.6	P4SR:24.00 ₃		0	P4SR:25.50 ₃	
Climate sequence 4			Climate sequence 5		
0	P4SR:18.00 ₁	7.75	1.2	P4SR:17.00 ₁	5.00
1.2	P4SR:25.75 ₃	.75	0	P4SR:22.00 ₂	3.75
0.6	P4SR:26.50 ₂		0.6	P4SR:25.75 ₃	
Climate sequence 6			Critical HSD-values		
0.6	P4SR:11.00 ₁	8.75*	1.2	HSD 0.05;3,36 = 7.79	
0	P4SR:19.75 ₃	0.25		HSD 0.01;3,36 = 9.91	
1.2	P4SR:20.00 ₂				

Appendix Table 9. Analysis of variance of Retention 2 and tests of simple main differences between climate sequences within the 0.6 P4SR climate and between climates within climate sequences 1, 3, 4, 5, and 6 (* denotes 0.05, ** denotes 0.01 and *** denotes 0.001 statistical significance; subscripts denote order of presentation).

Source	SS	df	MS	F
1	171556.982	23		
2	57358.570	5	11471.714	1.81
3	114198.412	18	6344.356	
4	7190.667	3	2396.889	
5	9214.250	3	3071.417	
6	45734.920	3	15244.973	C = 0.40
7	13584.918	3	4528.306	
8	27353.000	3	9117.666	
9	11120.667	3	3706.889	
10				
11				
12				
13				
14	17043.327	48		
15	2195.528	2	1097.764	4.14 [*]
16				
17				
18				
19				
20				
21				
22	1837.700	1	1837.700	6.89 [*]
23	.357.840	1	357.840	1.36
24	5311.971	10	531.197	2.01 ^o
25	1938.400	5	387.680	1.45 ^o
26	3373.560	5	674.712	2.57 ^o
27	9535.816	36	264.884	
28	2096.833	6	349.472	
29	2111.500	6	351.917	
30	1179.833	6	196.639	C=0.22
31	1207.333	6	201.222	
32	1850.500	6	308.417	
33	1089.833	6	181.639	
34	4803.400	18	266.856	
35	4732.400	18	262.911	
36	188600.309	71		

Mean differences				Critical HSD-value	Critical LSD-value
Climate	0.6	0	[*] HSD	HSD _{0.05;3,36} =11.50	LSD _{0.05;3,36} =9.54
1.2 P4SR:109.04	1.46	12.38	[*] HSD		
0.6 P4SR:110.50		10.92	[*] LSD		
0 P4SR:121.42					

Appendix Table 10. Analysis of variance of Addition: number of calculated items, and tests of mean differences between climates (^o denotes 0.1, and ^{*} denotes 0.05 statistical significance).

Source	SS	df	MS	F
1	94787.273	23	-	
2	28777.610	5	5755.522	1.57
3	66009.663	18	3667.204	
4	6206.000	3	2068.667	
5	680.250	3	226.750	
6	38558.250	3	12852.750	C=0.58*
7	1762.000	3	587.333	
8	17308.914	3	5769.638	
9	1494.250	3	498.083	
10		5		
11		5		
12		5		
13		54		
14	7089.969	48	-	
15	1779.694	2	889.841	7.88**
16		2		
17		2		
18		2		
19		2		
20		2		
21		2		
22	1150.500	1	1150.500	10.46**
23	629.170	1	629.170	5.43*
24	1245.972	10	124.597	1.10
25	568.100	5	113.620	1.03
26	677.830	5	135.566	1.17
27	4064.327	36	112.898	
28	893.500	6	148.916	
29	433.500	6	72.250	
30	530.000	6	88.333	C=0.23
31	919.999	6	153.333	
32	514.833	6	85.805	
33	772.500	6	128.749	
34	1978.900	18	109.939	
35	2085.500	18	115.861	
36	101877.242	71	-	

Mean differences			Critical HSD-values
Climate	1.2	0	
0.6 P4SR:67.63	1.37	11.16**	HSD _{0.05; 3, 36} =7.51
1.2 P4SR:69.00		9.79**	HSD _{0.01; 3, 36} =9.55
0 P4SR:78.79			

Appendix Table 11. Analysis of variance of Multiplication: number of calculated items, and tests of mean differences between climates (* denotes 0.05 and ** denotes 0.01 statistical significance).

Source	SS	df	MS	F
1	178.666	23		
2	71.833	5	14.367	2.42 ^o
3	106.833	18	5.935	
4	14.000	3	4.667	
5	22.000	3	7.333	
6	28.000	3	9.333	
7	12.250	3	4.083	C = 0.26
8	12.918	3	4.306	
9	17.667	3	5.889	
10	71.875	5	2.875	1.18
11	235.000	5	9.400	3.86**
12	166.875	5	6.675	2.74*
13	131.490	54	2.435	
14	49.334	48		
15	1.750	2	0.875	1.28
16	10.166	2	5.083	7.42**
17	2.166	2	1.083	1.58
18	2.166	2	1.083	1.58
19	1.500	2	0.750	1.09
20	7.166	2	3.583	5.23*
21	1.500	2	0.750	1.09
22	0.750	1	0.750	1.50
23	1.000	1	1.000	1.15
24	22.917	10	2.292	3.35**
25	11.250	5	2.250	4.50**
26	11.667	5	2.333	2.68 ^o
27	24.667	36	0.685	
28	6.569	6	1.094	
29	2.500	6	0.416	
30	6.500	6	1.083	C = 0.25
31	4.500	6	0.750	
32	4.833	6	0.805	
33	1.833	6	0.305	
34	9.000	18	0.500	
35	15.666	18	0.870	
36	228.000	71		

Simple mean differences

0.6 P4SR

Climate sequence	6	3	5	1	4
2:0.75	0.50	0.75	2.50* LSD	3.00** LSD	3.75** LSD
6:1.25		0.25	2.00	2.50* LSD	3.25** LSD
3:1.50			1.75	2.25* LSD	3.00** LSD
5:3.25				0.50	1.25
1:3.75					0.75
4:4.50					
S	(1+4) - (2+6) = 3.13*				

1.2 P4SR

Climate sequence	3	2	5	1	4	
6:1.25	0.00	0.25	0.25	1.50	3.25*	LSD
3:1.25		0.25	0.25	1.50	3.25*	LSD
2:1.50			0.00	1.25	3.00*	LSD
5:1.50				1.25	3.00*	LSD
1:2.75					1.75	
4:4.50						

Critical HSD'-values	Critical LSD'-values	Critical S'-values
HSD' = 3.28 0.05	LSD' = 2.22 0.05	S' = 2.35 0.05 (1+4) - (2+6) + (3+5)
HSD' = 3.96 0.01	LSD' = 2.97 0.01	S' = 2.81 0.01 (1+4) - (2+6) + (3+5)
		S' = 2.72 0.05 (1+4) - (2+6)
		S' = 3.25 0.01 (1+4) - (2+6)

Climate sequence 1	1.2	0.6	Climate sequence 5	0	0.6
0 P4SR:1.50 ₁	1.25	2.25**	1.2 P4SR:1.50 ₁	1.50*	1.75*
1.2 P4SR:2.75 ₂		1.00	0 P4SR:3.00 ₂		0.25
0.6 P4SR:3.75 ₃			0.6 P4SR:3.25 ₃		

Critical HSD-values	
HSD = 1.43 0.05; 3,36	HSD = 1.82 0.01; 3,36

Appendix Table 12. Analysis of variance of APT: raw score and tests of simple mean differences between climate sequences within the 0.6 and 1.2 P4SR climates and between climates within climate sequences 1 and 5. (° denotes 0.1, * denotes 0.05, and ** denotes 0.01 statistical significance; subscripts denote order of presentation).

Source	SS	df	MS	F
1	2925.875	23		
2	1050.792	5	210.158	2.02
3	1875.083	18	104.171	
4	270.918	3	90.306	
5	489.582	3	163.194	
6	373.668	3	124.556	
7	91.584	3	30.528	C = 0.26
8	249.000	3	83.000	
9	400.335	3	133.445	
10	210.210	5	42.042	1.11
11	663.000	5	132.600	3.50**
12	475.335	5	95.067	2.51*
13	2043.252	54	37.838	
14	470.000	48		
15	4.083	2	2.042	< 1
16	127.166	2	63.583	13.61***
17	17.166	2	8.583	1.84
18	28.666	2	14.333	3.07 ^o
19	22.166	2	11.083	2.37
20	85.500	2	42.750	9.15***
21	21.166	2	10.583	2.27
22	1.021	1	1.021	< 1
23	3.063	1	3.063	< 1
24	297.750	10	29.775	6.37***
25	155.599	5	31.120	7.69***
26	142.147	5	28.429	5.37**
27	168.166	36	4.671	
28	50.833	6	8.472	
29	42.167	6	7.027	
30	33.333	6	5.555	C = 0.30
31	13.167	6	2.194	
32	12.500	6	2.083	
33	16.167	6	2.694	
34	72.880	18	4.049	
35	95.290	18	5.294	
36	3395.875	71		

Simple mean differences

O.6 P4SR

Climate sequence	2	3	5	1	4
6: 5.50	0.25	3.00	8.25	10.75* LSD	13.75** LSD
2: 5.75		2.75	8.00	10.50* LSD	13.50** LSD
3: 8.50			5.25	7.75	10.75* LSD
5: 13.75				2.50	5.50
1: 16.25					3.00
4: 19.25					
S (1+4) - (2+6) = 12.13*					

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1.2 P4SR

Climate sequence	5	2	3	1	4	
6: 7.25	0.50	0.75	1.75	6.75	12.25*	LSD
5: 7.75		0.25	1.25	6.25	11.75*	LSD
2: 8.00			1.00	6.00	11.50*	LSD
3: 9.00				5.00	10.50*	LSD
1: 14.00					5.50	
4: 19.50						

Critical HSD'-values	Critical LSD'-values	Critical S'-values
HSD' = 12.91 0.05	LSD' = 8.75 0.05	S' = 9.25 0.05 (1+4) - (2+6) + (3+5)
HSD' = 15.55 0.01	LSD' = 11.69 0.01	S' = 11.03 0.01 (1+4) - (2+6) + (3+5)
		S' = 10.67 0.05 (1+4) - (2+6)
		S' = 12.74 0.01 (1+4) - (2+6)

Climate sequence	1	1.2	0.6	Climate sequence	5	0	0.6
0 P4SR: 8.50 ₁		5.50**	7.75**	1.2 P4SR: 7.75 ₁		5.25**	6.00**
1.2 P4SR: 14.00 ₂			2.25	0 P4SR: 13.00 ₂			0.75
0.6 P4SR: 16.25 ₃				0.6 P4SR: 13.75 ₃			

Critical HSD-values	
HSD = 3.74 0.05; 3,36	HSD = 4.76 0.01; 3,36

Appendix Table 13. Analysis of variance of APT: bonus score and tests of simple mean differences between climate sequences within the 0.6 and 1.2 P4SR climates and between climates within sequences 1 and 5 (0 denotes 0.1, * denotes 0.05, ** denotes 0.01, and *** denotes 0.001 statistical significance; subscripts denote order of presentation).

Source	SS	df	MS	F
1	1391.319	23		
2	64.569	5	12.914	< 1
3	1326.750	18	73.708	
4	132.918	3	44.306	
5	80.250	3	26.750	
6	545.667	3	181.889	
7	190.333	3	63.444	C = 0.41
8	291.333	3	97.111	
9	86.250	3	28.750	
10	59.210	5	11.842	< 1
11	110.210	5	22.042	< 1
12	223.375	5	44.675	1.47
13	88331.472	54	30.292	
14	644.000	48		
15	6.778	2	3.389	< 1
16	31.500	2	15.750	1.84 ^o
17	43.166	2	21.583	2.51 ^o
18	28.166	2	14.083	1.64
19	90.500	2	45.250	5.27**
20	57.166	2	28.583	3.33*
21	84.500	2	42.250	4.92*
22	1.333	1	1.333	< 1
23	5.444	1	5.444	< 1
24	328.222	10	32.822	3.82**
25	161.167	5	32.233	4.16*
26	167.056	5	33.411	3.55*
27	309.000	36	8.583	
28	43.833	6	7.305	
29	53.500	6	8.916	
30	25.833	6	4.305	C = 0.27
31	80.167	6	13.361	
32	22.167	6	3.694	
33	83.500	6	13.916	
34	139.500	18	7.750	
35	169.500	18	9.417	
36	2035.318	71		

Simple mean differences

Climate sequence 4	0.6	1.2	Climate sequence 5	0	0.6
0 P4SR:15.75 ₁	1.75	6.50**	1.2 P4SR:12.75 ₁	3.50	5.25*
0.6 P4SR:17.50 ₂		4.75	0 P4SR:16.25 ₂		1.75
1.2 P4SR:22.25 ₃			0.6 P4SR:18.00 ₃		
Climate sequence 6	1.2	0	Critical HSD-values		
0.6 P4SR:13.50 ₁	3.25	6.50**	HSD _{0.05;3,36}	=5.07	
1.2 P4SR:16.75 ₂		3.25	HSD _{0.01;3,36}	=6.45	
0 P4SR:20.00 ₃					

Appendix Table 14. Analysis of variance of Partington 1 and tests of simple mean differences between climates within climate sequences 4, 5 and 6 (^o denotes 0.1, * denotes 0.05 and ** denotes 0.01 statistical significance; subscripts denote order or presentation).

Source	SS	df	MS	F
1	2373.111	23		
2	188.444	5	37.689	< 1
3	2184.667	18	121.370	
4	250.000	3	83.333	
5	534.250	3	178.083	
6	826.250	3	275.417	
7	25.668	3	8.556	C=0.38
8	511.584	3	170.528	
9	36.918	3	12.306	
10				
11				
12				
13				
14	1169.333	47		
15	143.361	2	71.681	3.69*
16				
17				
18				
19				
20				
21				
22	13.021	1	13.021	< 1
23	130.340	1	130.340	7.48**
24	345.139	10	34.514	1.77
25	27.354	5	5.471	< 1
26	317.780	5	63.556	3.65*
27	680.833	35	19.452	
28	82.500	5	16.500	
29	57.500	6	9.583	
30	224.000	6	37.333	
31	104.833	6	17.472	C=0.32
32	146.167	6	24.361	
33	65.833	6	10.972	
34	367.125	18	20.396	
35	313.710	18	17.428	
36	3542.444	70		

Mean differences			Critical HSD-values
Climate	1.2	0.6	HSD _{0.05;3,35} = 3.12
0 P4SR:18.75	1.04	3.38*	
1.2 P4SR:19.79		2.34	HSD _{0.01;3,35} = 3.97
0.6 P4SR:22.13			

Appendix Table 15. Analysis of variance of Partington 2 and tests of mean differences between climates (* denotes 0.05 and ** denotes 0.01 statistical significance).

Rank	Subject	Factor						
		1	2	3	4	5	6	7
1	5	-.02	.75	.16	.11	.20	.17	.01
2	7	.03	.06	.16	.01	.26	.05	.65
3	6	.22	.25	.62	.21	.31	-.11	.01
4	2	-.21	.01	-.08	.37	.01	.69	-.08
6	3	.02	.32	.69	-.09	.06	-.05	.22
6	14	.33	.62	.18	.03	-.04	-.24	.28
6	22	.03	.29	.04	-.12	.71	.00	.16
8	24	-.01	.36	-.25	.01	-.03	.70	.06
9	23	-.14	.17	.50	-.15	-.12	.44	.47
10	1	.23	-.06	.18	-.17	-.03	.79	.13

11	21	.22	.06	.10	.03	.72	-.10	.09
12,5	4	.07	-.10	.08	.02	.58	.59	.04
12,5	8	.04	.59	.22	-.05	.32	.28	-.25
15	13	-.05	.08	.37	.39	.15	.16	.36
15	18	.25	-.02	-.08	.43	.45	.19	.43
15	20	.46	.58	.11	.00	-.01	-.08	.14
17	17	.66	.09	.06	.17	.13	.15	.21
18	19	-.20	-.31	.09	.60	-.04	.48	.18
19	9	.72	.12	-.29	.05	.13	-.14	.14
20	12	.24	.11	-.04	.79	-.08	.02	.09
21	11	.79	.04	.12	.16	.15	-.02	-.19
22,5	10	.25	.24	-.41	.62	.19	-.08	.09
22,5	16	.25	-.05	.13	.74	-.07	-.08	-.20
24	15	.62	.13	.16	.40	.04	.08	-.30
Variance proportion		.20	.13	.11	.07	.06	.05	.04

Appendix Table 16. Rotated Q-factor matrix. The subjects are ranked with respect to performance change on Learning 2 at 0.6 P4SR; subjects ranked 10 or less improved their performance under heat load.

Rank	Subject	F a c t o r					
		1	2	3	4	5	6
1	8	-.04	.31	.10	.06	.17	.68
2	1	-.23	.78	.21	.12	-.07	-.12
3	4	.01	.61	.10	-.05	.45	-.01
4	5	.10	-.04	.21	.09	.08	.80
5	13	.12	.23	.60	.00	.15	.07
7.5	3	-.06	-.04	.71	.18	-.05	.33
7.5	6	.14	-.15	.53	.30	.15	.30
7.5	7	.01	-.09	.61	-.12	.45	-.12
7.5	23	-.15	.31	.79	-.16	-.02	.10
10.5	21	-.00	.04	.01	.29	.66	.12
10.5	22	-.15	.07	.14	.07	.69	.36
12	2	.43	.63	.05	-.20	.10	.01
13	24	.03	.76	-.03	.05	.02	.25

14.5	9	-.06	-.11	-.15	.76	.24	-.04
14.5	19	.57	.47	.26	-.27	.01	-.26
16	11	.25	.05	-.04	.75	.17	-.05
17	18	.33	.17	.25	.27	.64	-.12
18	14	.15	-.29	.18	.48	.00	.41
20	15	.32	-.03	-.04	.70	-.03	.14
20	17	.14	.16	.16	.64	.19	.06
20	20	-.04	-.07	.14	.58	-.04	.37
22	12	.71	.08	.09	.25	.01	.02
23	10	.62	-.12	-.27	.26	.27	.22
24	16	.78	-.10	-.03	.21	-.13	.02

Variance proportion		.20	.15	.10	.07	.06	.05

Appendix Table 17. Rotated Q-factor matrix. The subjects are ranked with respect to performance change on Retention 2 at 0.6 P4SR; subjects ranked 13 or less improved their performance under heat load.

Rank	Subject	Factor						
		1	2	3	4	5	6	7
1	5	.08	.52	-.11	.41	.31	.20	-.28
2.5	6	.09	.36	.22	-.04	.65	.01	-.10
2.5	7	.17	.24	.05	-.08	.12	.67	.00
5	1	.02	-.01	.27	.76	.06	.06	.26
5	2	.58	-.14	-.01	.52	.02	.14	-.41
5	8	-.02	.25	.11	.49	-.20	.58	-.04
7.5	3	-.17	.06	-.09	-.02	.80	.23	.16
7.5	22	-.06	.12	.37	.08	.20	.60	.13
9	24	.10	.08	-.00	.83	-.05	-.02	-.08
11.5	14	.02	.73	.02	-.02	.16	.16	.13
11.5	20	-.21	.60	.09	.13	.06	.26	.01
11.5	21	-.01	.41	.44	-.16	.16	.25	-.06
11.5	23	-.07	-.06	-.17	.33	.37	.53	.34

15.5	4	.28	-.11	.56	.35	.28	.21	.01
15.5	9	.14	.56	.48	.02	-.08	-.35	.22
15.5	15	.34	.05	.61	.03	-.04	.12	-.28
15.5	18	.56	.29	.30	.09	.33	.04	.07
18	12	.74	-.19	.17	.15	-.05	-.04	.28
19	11	.13	.10	.81	-.02	-.19	-.01	-.03
20	16	.80	.03	.12	-.16	-.19	.11	-.07
21.5	13	.40	.19	-.05	.05	.12	.27	.65
21.5	19	.73	-.40	.01	.15	.21	.02	.12
23.5	10	.66	.25	.29	.09	-.16	-.15	-.01
23.5	17	.10	.02	.73	.17	.15	.07	.11

Variance proportion		.21	.14	.10	.07	.06	.05	.04

Appendix Table 18. Rotated Q-factor matrix. The subjects are ranked with respect to performance change of APT: bonus score at 0.6 P4SR; subjects ranked 11.5 or less improved their performance under heat load.

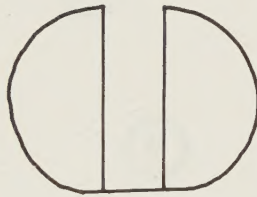
Rank	Subject	F a c t o r							
		1	2	3	4	5	6	7	8
1.5	1	.10	.02	-.01	.78	.02	-.03	.17	-.15
1.5	3	.12	.72	.03	.11	.21	.03	-.15	-.14
3	16	.11	.01	-.07	.15	.11	.74	.25	.21
5	2	-.01	-.04	.48	.55	-.06	.27	.13	-.06
5	4	-.11	.30	.09	.67	.13	-.07	-.21	.22
5	6	-.10	.60	.12	.17	.06	-.02	.02	.38
7	13	-.09	.19	.49	.13	.14	.60	-.08	-.07
8.5	8	.07	.27	-.08	.67	.03	.24	-.04	.18
8.5	11	.01	-.08	-.16	.16	.45	.05	.67	.10
11	5	.24	.68	-.10	.32	.04	-.00	.05	-.11
11	17	-.03	.39	.18	.21	.53	-.23	.30	.10
11	21	.14	.06	.18	-.03	.75	.27	.02	.13

13.5	9	.03	-.02	-.10	-.18	-.06	.09	.49	.55
13.5	15	-.00	-.04	.02	.23	.28	.00	.18	.68
15.5	10	.20	-.04	.25	-.03	.03	.10	.78	.02
15.5	20	.77	.14	-.03	-.02	.19	.02	.15	.06
18	7	-.08	.66	.14	-.10	-.27	.34	.16	.06
18	14	.52	.06	.01	-.07	.00	.15	-.03	.68
18	24	.63	-.04	.40	.35	-.17	.01	.20	.11
21	18	.16	.07	.75	-.07	.06	-.18	.21	.15
21	22	.05	-.03	.71	-.07	.31	.02	.01	.29
21	23	.07	.36	.53	-.10	.05	.41	-.06	-.17
23	19	-.06	.00	.78	.14	-.03	.12	.13	-.13
24	12	.12	.24	.39	.13	-.09	.04	.61	.27
Variance proportion		.21	.11	.09	.07	.05	.05	.05	.04

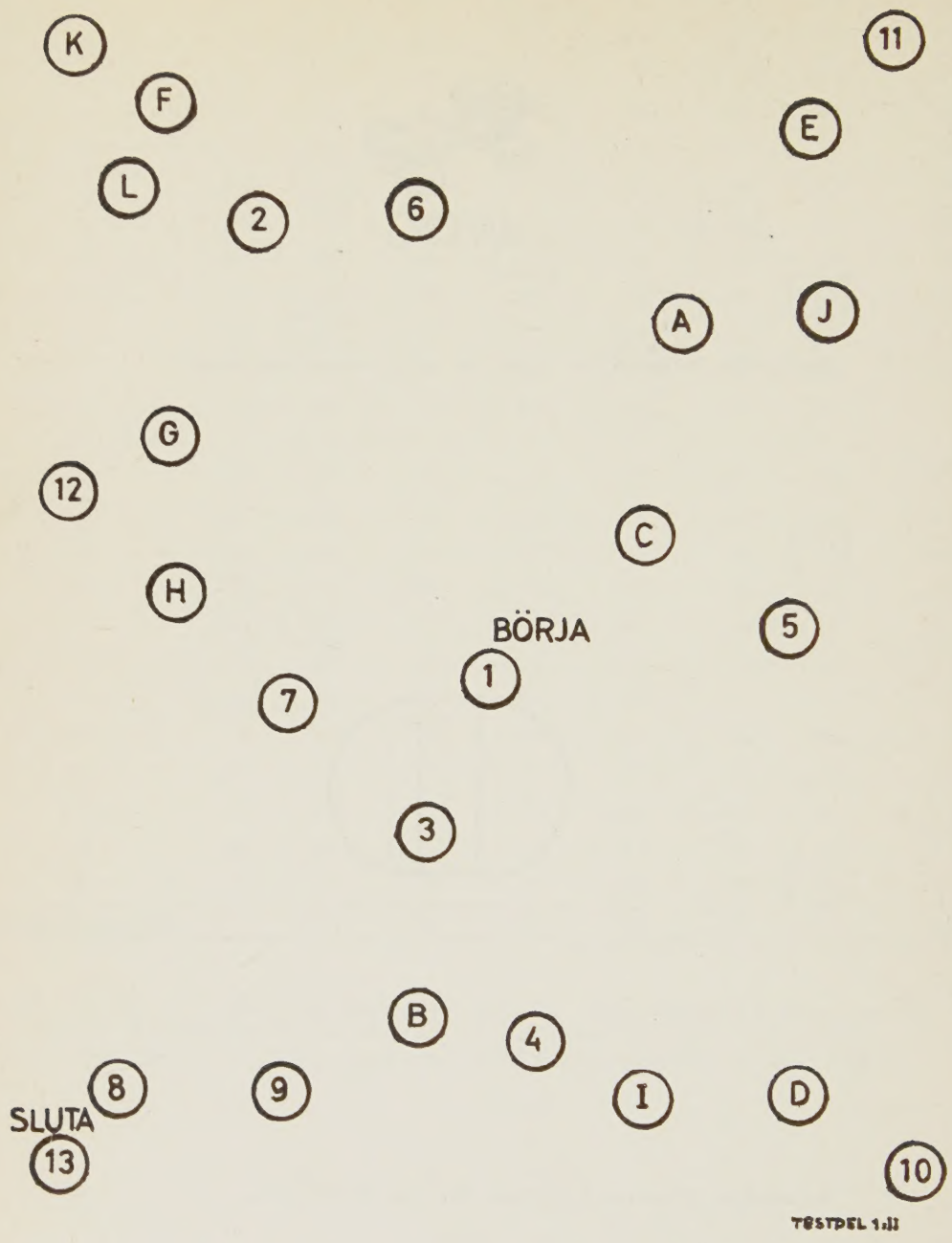
Appendix Table 19. Rotated Q-factor matrix. The subjects are ranked with respect to performance change on Partington 1 at 1.2 P4SR; subjects ranked 11 or less improved their performance under heat load.



Appendix Figure 1. Item of the Learning task.



Appendix Figure 2. Item of the APT film.



Appendix Figure 3. Partington's Pathways Test - Partington 2

D4:1975

Document D4:1975 refers to a research grant from The National Swedish Board of Education to the National Swedish Institute for Building Research 1966/67, aiming at a design guide for school-buildings.

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